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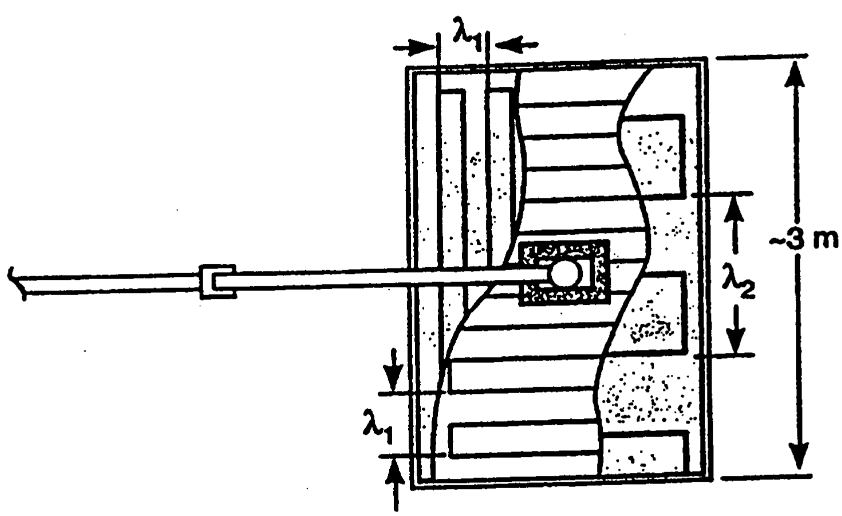
(54) Title: MAGNETOMETER AND DIELECTROMETER DETECTION OF SUBSURFACE OBJECTS



(57) Abstract

A detection apparatus discriminates between metallic mines and other buried objects by detecting the depth of the object, the size, the shape and the orientation of the object and the electrical properties of the object. A dielectric sensor having a first electrode and a second electrode is used in one embodiment. The first electrode is driven with a varying voltage to establish a varying electric field through the ground to the second electrode. The voltage magnitude and phase of the second electrode are measured. Another apparatus, a magnetometer sensor, detects objects containing metal located below the surface of the ground. This apparatus has a plurality of parallel, spaced linear conductor sets disposed in proximity to the ground. An electromagnetic field is imposed in the ground with a dominant spatial wavelength through the conductor elements. A resulting electromagnetic response of the object in the ground to the imposed magnetic field is sensed. The conductor sets may have varying number of individual conductors.

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Magnetometer and Dielectrometer Detection of Subsurface Objects

RELATED APPLICATION(S)

This application claims benefit of U.S. Provisional Application Serial No. 60/064,808 filed November 7, 1997, U.S. Provisional Application Serial No. 60/043,695 filed April 15, 1997, and U.S. Provisional Application Serial No. 60/034,541 filed January 6, 1997, the entire teachings of which are incorporated herein by reference.

GOVERNMENT SUPPORT

The invention was supported, in whole or in part, by Contract Number DAAB07-97-C-J002 from Department of the Army. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

According to the United Nations, there are over 100 million land mines currently deployed in more than 60 countries. The mines themselves range from large anti-tank mines to small anti-personnel mines and from all metal construction to primarily plastic or even wood. Triggering

mechanisms range from direct pressure, to trip wires to magnetic sensors and fiber optics.

In addition, millions of bomblets were deployed as Cluster Bomb Units (CBUs) during wars and military actions. A significant number of these failed to explode and continue to threaten the populations indigenous to the original combat zones. Being largely constructed of metal, unexploded bomblets are readily detectable with existing hand-held metal detectors. However, current metal detectors have no way of discriminating an intact bomblet, which may be buried at depths up to 12 inches, from a bomblet fragment or other piece of shrapnel or metallic debris that is near the surface.

The US Army currently has a deployed mine detector called the AN/PSS-12. This is an inductive type detector that utilizes the creation of eddy currents in a metallic mine to alter the search coil impedance. This detector has served the Army well, but to be reliably detected, mines must be directly below the search head and must contain some metal. Other methods such as ground penetrating radar, infrared, and X-Ray have been investigated to solve the difficult problem of detecting low-metal and no-metal mines.

SUMMARY OF THE INVENTION

This invention relates to detection apparatus and methods which are capable of discriminating between mines, bomblets and other objects buried below the surface of the ground by detecting object depths, sizes, shapes, orientations and/or electrical properties. An inductive magnetometer is best suited to detecting and characterizing metallic objects; whereas, a capacitive dielectrometer is particularly effective in detecting and characterizing nonmetallic objects.

In the preferred magnetometer, a plurality of parallel, spaced linear conductor sets are disposed in proximity to the ground. An electromagnetic field is imposed in the ground with a dominant spatial wavelength through the conductor sets. A resulting electromagnetic response of the object in the ground to the imposed magnetic field is sensed. The method, in a preferred embodiment, also includes the step of translating electromagnetic response into estimates of one or more properties of the object based on a modeled response to the spatial wavelength.

In a preferred magnetometer embodiment, the dominant spatial wavelength has a length of at least 12 inches. The apparatus also has a rigid conductor element support structure adapted to be scanned across the ground.

In a preferred magnetometer, a primary winding has a series of parallel, spaced linear conductor sets driven by a current. The number of parallel conductors in the parallel conductor sets varies so as to shape the applied magnetic field. The applied field is periodic sinusoidal in a preferred embodiment.

The sensor in a preferred embodiment is an array of secondary windings. At least one of the secondary windings is located between parallel conductor sets of each pair of adjacent parallel conductor sets of the primary winding. The apparatus may have a second secondary array and primary winding which is perpendicular to the first set of parallel conductors of the first primary winding.

In a preferred embodiment of the dielectrometer apparatus, an excitation electrode carried on a sensor face is driven with a varying voltage, and a sensing electrode is carried by the sensor face. A guard electrode of the sensor face surrounds the sensing electrode and is at about the same voltage as the sensing electrode.

A shielding plane is located behind and spaced from the sensor face for blocking unwanted interference in one of the preferred embodiments of the dielectrometer apparatus. A guard plate is also interposed between the shielding plane and the guard electrode. A high-impedance buffer is connected to the sensing electrode to measure the magnitude and phase of the floating potential. The sensor face has an area of at least a square foot for mine detection but could be used in a smaller form for other applications, such as cure monitoring of thin coatings.

In one preferred embodiment of the dielectrometer apparatus, the sensing electrode has a plurality of elements in a column at different distances to the excitation electrode. In another preferred embodiment, the sensing electrode has a plurality of elements in a row wherein each element is equidistant to the excitation electrodes. The elements may be connected such that differences in measurements between adjacent elements can be used to detect small spatially abrupt changes in the dielectric properties, and to account for variations in stand-off distance from the sensor to the soil surface.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

Figure 1 is a schematic illustration of a Meandering Winding Magnetometer (MWM);

Figure 2A illustrates the MWM Sensor;

Figure 2B illustrates a "Standing Wave" of Magnetic Vector Potential, A_z, produced by the Dominant Fourier Mode, Corresponding to the A_1 Fourier Amplitude;

Figure 3 shows a Meandering Winding Magnetometer sensor of conductive material on a nonconductive substrate;

Figure 4 an array of Secondary Windings, x_1 through x_8 with Corresponding Areas of Sensitivity A_{x1} through A_{x8};

Figure 5 illustrate orthogonal arrays of secondary windings, with the corresponding meandering primary windings;

Figure 6A illustrates a deep penetration primary winding schematic;

Figure 6B illustrates a preferred wiring pattern of the deep penetration primary winding for shaping the sinusoidal;

Figure 7A illustrates a two wave length, two orientation MWM detector;

Figure 7B illustrates a cross section of the sensor over a mine;

Figure 8A shows a top view of a sensor with the conductor sets all having current flowing in the same direction;

Figure 8B illustrates a cross section of the conductor sets and the spatial wavelength;

Figures 9A and 9B illustrate conductivity lift-off grids for (a) Aluminum and (b) Carbon Steel;

Figure 10A illustrates interdigitated electrode dielectrometer (IDED) sensor;

Figure 10B illustrates a plan view of the IDED sensor;

Figures 11A and 11B show two IDED sensors with different electrode spacing illustrating that the spacing effects the sensitive to different depths into the material under test;

Figure 11C illustrates an IDED sensor with an array of sensing electrodes;

Figure 12 illustrates the IDED characterization of a multiple layer material;

Figure 13 illustrates a single sensing electrode IDED sensor;

Figure 14 illustrates the equi-potential lines and electric field lines of sensor cross-section;

Figure 15A is a cross section of a sensor with multiple sensing elements positional side-by-side for multiple depths;

Figure 15B is a perspective view of a sensor with a multiple sensing elements positioned in-line;

Figure 15C is a cross section of a sensor having a guard plate;

Figure 16 is a simplified schematic of the detector drive and the feed back sensor;

Figure 17A shows the scanning results of the sensor shown in Figure 16B with a plastic mire buried in sand to increasing depths;

Figure 17B shows the scanning results conducted at different times;

Figure 17Ca shows the scanning of a mine and a rock;

Figure 17Cb shows the scanning of a metallic bomblet;

Figure 18 illustrates a circular center electrode surrounded by a coplanar, concentric electrode, a "Bull's Eye" Sensor;

Figure 19A illustrates a helicopter deployment of a roadway sensor for rapid minefield breaching;

Figure 19B illustrates a tape dispensed sensor suitable for path clearing;

Figure 20 shows a mechanically adjustable wavelength sensor;

Figure 21A illustrates that the dielectric constants of mine materials and soils converge at higher frequencies and diverge at lower frequencies;

Figure 21B illustrates that conductivity is frequency dependent for soils and plastic mine materials and much higher at high frequencies;

Figure 22A illustrates that the computed sensor capacitance change (decrease) due to buried plastic layer in dry sand; and

Figure 22B illustrates that the computed change (increase) in sensor capacitance from simulated metal mine (layer construct) in dry sand.

DETAILED DESCRIPTION OF THE INVENTION

This invention relates to two new sensing capabilities that are complementary and both field deployable and supportable. The first sensing capability is magnetoquasistatic, an inductive sensor, which will be referred to as Meandering Winding Magnetometer (MWM). The second sensing capability is an electroquasistatic, capacitive sensor which will be referred to either as an Interdigitated Electrode Dielectrometer (IDED) for periodic constructs or as a dielectrometer for non-periodic constructs. The sensors individually have certain capabilities to determine the depth, material type, size and orientation of a subsurface object as described below. The synergy of the two sensors allows further capability.

The principal surface considered is that interface between air and ground, wherein the ground is a mixture of one or more of dirt, sand, rock, moisture and other such materials. A subsurface object is generally an object which is located within 2 feet of the surface and particulary within 12 inches.

Meandering Winding Magnetometer (MWM) Sensor

The magnetoquasistatic sensing capability using a Meandering Winding Magnetometer (MWM) will be described first. The MWM comprises a meandering primary winding, with one or more secondary windings such as the meandering secondary on each side of the primary as illustrated in Figure 1. The MWM is essentially a planar transformer, in which the primary winding is inductively coupled with the secondary winding through the neighboring material.

The secondary windings, which meander on opposite sides of the primary, are connected in parallel to reduce capacitive coupling and to maintain symmetry as illustrated in Figure 2A. The winding spatial wavelength is indicated by λ. A current, i_1, is applied to the primary winding and a voltage, v_2, is measured at the terminals of the secondary windings.

The shape of the MWM windings produces a spatially periodic magnetic field as shown in Figure 2B. The spatial periodicity of the field is a key attribute of the MWM and is the principal reason it can be modeled with such accuracy. The MWM continuum models permit precise determination of depth and material properties for detected objects.

The MWM is tailored such that the magnetic vector potential produced by the current in the primary winding can be accurately modeled as a Fourier series summation of

sinusoids in Cartesian (x,y,z) coordinates. The tailoring is described in further detail in United States Patent No. 5,453,689 titled "Magnetometer Having Periodic Winding Structure and Material Property Estimator" which issued on September 26, 1995, the entire contents of which are incorporated herein by reference.

In the magneto-quasistatic regime, the MWM primary winding produces a sinusoidal "standing wave" magnetic vector potential. The spatial wavelength of this standing wave is determined by the MWM primary winding geometry and is independent of the input current temporal frequency. The fundamental Fourier mode wavelength is equal to the physical, spatial wavelength of the MWM primary winding, as shown in Figure 2B. The uniform standing wave field produced by the MWM sensor maintains its shape over a significant footprint area. Thus, for MWMs with multiple periods (i.e., more than four) a subsurface object, such as a bomblet, will produce the same MWM response at all locations within the MWM footprint (i.e., < ½ wavelength from the edge of the sensing region).

The MWM sensors can be fabricated in several embodiments. These can have either multiple periods, a single period (i.e., only one period of a sine wave is produced by the field shaping primary), or a fraction of a period (e.g. half). While the embodiments will be described with respect to preferred embodiments for a particular size range, such descriptions are not meant to limit particular sizes to particular embodiments.

One embodiment of sensors is fabricated by deposition and selective removal of a conducting material on a thin film nonconducting substrate as seen in Figure 3. This printed conducting material is considered a wire. This

method of sensor construction allows the sensor to be very thin and of very low mass.

An alternative embodiment of sensor is to use a series of wires coiled into a desire pattern. This embodiment is a preferred embodiment for sensors having a surface area over a square foot. In a preferred embodiment the sensor is approximately 32 in. x 24 in., with only one primary winding period.

In certain embodiments of the over square foot array, arrays of secondary windings elements provide spatial resolution of indications on the order of an inch. This effectively maps the individual metallic components under the MWM footprint, permitting discrimination of an intact bomblet from bomblet fragments, shrapnel, or other metallic debris. This array construct also permits the use of multiple turn (coil) sensing elements (also called secondary windings) in the form of elongated coils. Thus, a large wavelength drive is used to provide deep penetration, while multiple sensing elements are used to provide high spatial resolution.

Figure 4 shows an array of secondary windings confined to a single plane. The individual windings in this array are designated x_1 through x_8. (The associated primary winding is not shown in this figure.) Ideally, each individual secondary winding would be sensitive <u>only</u> to conducting material in an elongated area, shown as A_{x1} through A_{x8}, in Figure 4. In practice, however, the secondary winding elements will be somewhat affected by objects located outside of these regions, as well. Thus, a more complex computation will be required to create accurate images of detected objects.

Windings can be stacked for increased output. For example, the array shown in Figure 4 can be repeated in

successive layers. The output of each illustrated coil, such as X_1 crosses over to the input of the next lower coil such that a stack of turns X_1 result in a spiral coil. In order that the array follows the model closely, the thickness between coil planes should be small relative to the wavelength of the array.

Figure 5 illustrates an orthogonal combination of two secondary winding arrays. These arrays, along with the associated meandering primary windings also shown in the figure, are stacked in one embodiment of the bomblet discrimination sensor to provide the mechanism for locating and sizing detections.

The typical required depth of penetration for the detection of subsurface weapons such as land mines and bomblets is six to twelve inches from the surface. A rule of thumb for the depth of penetration of the MWM fields is that the maximum field penetration is approximately one half wavelength from the sensor winding plane. The 24 inch by 24 inch MWM, with the orthogonal sensing arrays described above and as shown in Figure 5, has a wavelength of 6 inches and has a depth of penetration of only 3 inches.

For those situations where a deeper penetration of detection is required, a deep penetration winding as shown schematically in Figure 6A may be used. The deep penetration winding is composed of multiple parallel conductors, half of which carry current in one direction while the other half carry current in the opposite direction. By controlling the current carried by each conductor, this winding design can produce a single period of a sinusoidal magnetic field over the MWM sensing region with a spatial wavelength of 32 inches in the preferred embodiment for a particular bomblet's type. This design

can also provide shorter wavelength excitations, i.e., 12 inches, by electronically changing the current directions without changing the physical winding dimensions. This permits the use of multiple spatial wavelength excitations and performance of spectral analysis in space (instead of time) to improve clutter suppression and detection probability. This multiple wavelength interrogation approach is described in greater detail in U.S. Patent No. 5,015,951 titled "Apparatus and Methods for Measuring Permeability and Conductivity in Material using Multiple Wavenumber Magnetic Interrogations" which issued on May 14, 1991, the entire contents of which are incorporated herein by reference.

The deep penetration winding permits detection of bomblets to a depth of up to 16 inches from the surface, one half its maximum spatial wavelength. The secondary array, as discussed above with respect to the six inch wavelength MWM described in Figure 4, can be used with either the six inch wavelength MWM primary or with the deep penetration primary winding design. The secondary array permits better spatial resolution than the use of larger sensing elements.

By changing the connections of the parallel conductors, either through hard wired connections or switching, the wave length of the sensor array can be varied from a maximum illustrated in Figure 6A, where a first half of the conductors conduct current in one direction and a second half conduct in the opposite direction, to a minimum as illustrated in Figure 2B.

The use of multiple MWM spatial wavelengths provides depth information on detected objects. For example, when the six inch MWM primary is excited, objects deeper than three inches will not be detected. Thus, a bomblet buried

at ten inches will only be detected when the deep penetration primary is excited. This provides a clear capability to discriminate between small metallic objects near the surface and bomblets buried far below the surface.

A preferred wiring pattern of the deep penetration primary winding for shaping the sinusoidal wave is shown in Figure 6B. The primary winding has a series of parallel, spaced sets of linear conductors for receiving current. Each conductor set has at least one wire. The number of parallel wires in each set increases from 1 to 2 to 3 and then back down to 1 before the center line. The number of parallel wires in a set then progresses back to 3 and back down to 1 in the second half wavelength.

Those wires on the left side of the centerline of the sensor have the current flowing up the page as seen in Figure 6B. Those wires on the right side of the page have the current flowing down the page. The varying numbers of wires in each set and the flow of the current results in a deep penetrating electromagnetic waveform that has a single wavelength equal to the size of the sensor.

An array of secondary windings is illustrated in Figure 6B. At least one secondary winding is located between each adjacent pair of parallel conductors of the primary winding. In a preferred embodiment, the wires of the primary winding and the secondary windings are insulated metal conductors.

The sets of parallel wires in one embodiment are equally spaced. In another embodiment the spacing of the wires is also varied to shape the applied magnetic field.

A multiple wavelength MWM sensor configuration is shown in Figure 7A. The MWM sensor stack shown includes two different winding spacings (λ_1, λ_2) and two different orientations. Since the spacing of the MWM windings

determines the depth of penetration, this permits a real-time determination of depth and an estimate of aspect ratio as discussed below. Figure 7B illustrates the sensor of Figure 7A over a land mine.

Figures 8A and 8B show a sensor that has a plurality of conductor sets formed of wire. Each conductor set has the same number of wires. The current in each conductor set 90 is flowing in the same direction, up the page as seen in Figure 8A and into the page as seen in Figure 8B. The result is a uniform field in the central sensing region where spatial wavelength is essentially infinite. The spatial waves have been predominately described above as having a sinusoidal shape. It is recognized that other spatial waves may be desired in certain instances such as saw tooth waves, square waves, pulsed, and impulse. The width of the spatial wave can also vary. The wave can likewise increase or decrease as the wave progress over the sensor.

The MWM sensor is driven by an AC current and its response is measured by an impedance analyzer. In a preferred embodiment, a circuit board-level, multi-frequency impedance instrument having a range of 250 KHz - 2.5 MHZ is used. The response is compared to the continuum models. The sensor response which is in the terms of impedance phase and magnitude is converted into material properties or conditions of interest, such as conductivity and proximity. Proximity is the average distance between the winding plane and the surface of the conducting buried object.

In addition to permitting precise determinations of material properties, the MWM modeling software also incorporates methods to identify operating conditions that provide maximum sensitivity and selectivity (the ability to

measure two or more properties independently), without running extensive experiments. The identification of operating condition is described in further detail in United States Patent No. 5,015,951 titled "Apparatus and Methods for Measuring Permeability and Conductivity in Materials Using Multiple Wavenumber Magnetic Interrogations" which issued on May 14, 1991 and a United States patent application serial no. 08/702,276 titled "Meandering Winding Test Circuit" and filed on August 23, 1996, the entire contents of which are incorporated herein by reference.

Once an object is detected, the depth below the surface, and the size and shape of the object need to be ascertained in order to determine how to proceed. For example, if it is determined that the object is an intact mine or bomblet, the object needs to be marked, disarmed or removed. However, if it is determined that the object is fragment or debris, the object could be left.

One of the keys to discrimination will be determination of depth of an object of unknown size. For example, a small metal object located near the surface may be detected by more than one sensing element, as would a large object located far from the surface. Thus, to differentiate between these objects, depth information is required. Using model-based MWM grid measurement algorithms, the depth of a metallic object detected by an individual secondary (sensing) element can be determined. Also, an object's size and shape can be determined by combining information about the proximity of the object to the sensing elements with the number and location of the sensing elements that detected the object. Additional information may also be provided by the magnitude and phase of the detection signal at different input current

frequencies, and for different sensing element orientations. This additional information is used to increase detection sensitivity and to improve clutter suppression.

MWM can discriminate the location and the properties of the object by using some or all of the following approaches: (1) Spatial imaging; (2) Grid measurement algorithms; (3) Spectral analysis, spatial and temporal; and (4) a scanning or roving sensing element. The roving sensing element can be oriented either in a parallel or perpendicular plane to the MWM primary.

Spatial imaging approaches utilize the orthogonal array of secondary windings to provide spatial resolution and permit discrimination and analysis of multiple indications. The array output is operated upon by a logic module which applies the above analysis and is then used to drive a visual output display, discussed below, or an auditor signal to the operator. The visual display will provide the interface with the system operator.

Grid measurement algorithms permit the integration of impedance measurement data at multiple frequency, multiple winding spatial wavelengths, and multiple lift-offs (by moving the MWM sensor or using a roving sensing element). This integration is used in conjunction with the array calibration discussed below. The result is a multi-dimensional clutter suppression and bomblet identification algorithm that will provide robust, reproducible, and high confidence bomblet discrimination capability. It provides real-time (fast) measurements, enabled by table look-up from stored measurement grids.

Measurement grids are tables produced by the continuum models of the MWM and in a preferred embodiment are graphically displayed. The measurement grids are used to

convert the MWM impedance magnitude and phase measurements into material properties or material proximity. The real-time table look-up process is described in U.S. Patent Application Serial No. 08/702,276 which is titled "Meandering Winding Test Circuit" which was filed on August 23, 1996, the entire contents of which is incorporated by reference.

The grid measurement approach allows for detection and discrimination of various objects including various types of landmines and bomblets containing metal and other unexploded ordinance. The measurement grids also provide a unique tool for rapid field calibration of sensing arrays.

To generate measurement grids, the material conductivity (or other property of interest) is first estimated using calibration standards or values from the literature. (This estimate merely serves to define the general region of interest in which to run the models to generate predicted sensor response.) The continuum models of the MWM then predict sensor response, in terms of phase and magnitude, using the selected ranges of conductivity and proximity (lift-off). This type of grid is composed of lines of constant lift-off intersecting lines of constant conductivity. These grids are generated off-line and then provide a real-time (fractions of a second) measurement capability in the field.

Figures 9A and 9B illustrate measurement grids for aluminum and carbon steel. Note that the lift-off lines for aluminum are practically perpendicular to those of carbon steel. This offers a very direct approach for discriminating between steel and aluminum: simply vary the sensor lift-off (i.e., move it up and down relative to the ground) and observe the orientation of the lift-off line. This will provide a simple but effective filter for

eliminating aluminum objects, such as discarded containers, and other nonferrous metals from further consideration during bomblet discrimination. The system operator would only be required to move the sensor head vertically over an indication, while the software compares the lift-off response for the detected object to the stored lift-off response (in the measurement grid) generated off-line and calibrated for an intact bomblet.

Spectral analysis approaches involve operating MWMs of several spatial wavelengths at various excitation frequencies to provide more information about the sensed volume. The additional information from multiple grids obtained at different MWM spatial wavelengths and at multiple input current temporal frequencies can be used to determine the material type, size, depth and case thickness of the sensed object, as well as to further define and constrain the bomblet or landmine "signature", and improve clutter suppression and bomblet detection performance.

The scanning or roving sensor involves maneuvering a movable secondary winding (or electrode in the case of the dielectrometers) within the field of a fixed primary winding. This is an alternative approach to the use of multiple sensing elements to provide spatial imaging for discriminating intact bomblets.

The combination of MWM design and operational features with the grid measurement approach provides redundant paths to solution of the bomblet discrimination problem. Table 1 lists the system features and the information produced by each to support bomblet discrimination and clutter suppression. Each one of the four key attributes required to fully characterize an intact bomblet (size, shape, depth and material) can be generated by at least two of the system design or operational features.

SYSTEM OR OPERATIONAL FEATURES	DISCRIMINATOR
Secondary winding array*	Size, shape, depth
Multi-frequency measurements*	Material, size, depth
Multiple spatial wavelengths*	Depth
Multiple proximity measurements*	Material, size, depth
Rotating sensor head	Shape

* *When combined with measurement grids.*

Table 1. Bomblet discrimination features produced by MWM-Array System

The information gathered by the sensor needs to be displayed or disclosed to the user quickly and efficiently. The goal is to process the data and present the result in an unequivocal way that requires minimal operator interpretation. This will greatly reduce the training required for the user or operator.

A sensor array output may be located directly above the sensor. The display could be LED, LCD or other display device. The display is driven by two sensing elements, one in each of the orthogonal arrays. An LED is illuminated if both its associated sensing array elements detect a metallic object. An alternative embodiment to the sensors located directly above the sensor is a display located closer to the users.

Dielectrometer Sensor

While the magnetoquasistatic detection using the Meandering Winding Magnetometer is capable of determining

location, shape and orientation of metal, the MWM sensor is not capable of detecting plastic or other non-conducting objects within the ground. There exist many land mines that have very low metal content. Even if the MWM sensor was able to detect the metal, the size, shape and orientation of the metal detected would not allow the user of the sensor to ascertain whether the metal was or was not part of a land mine.

The second sensing capability, the dielectrometer, capacitive sensor is capable of detecting subsurface plastic as described below. The dielectrometer, capacitive sensor senses the dielectric properties of the material.

The dielectric properties of a material can be described by two parameters, the permittivity and conductivity. The permittivity describes the displacement current density produced in the material by an applied electric field, whereas the conductivity describes the conduction current density. The dielectric properties of materials vary significantly and can provide a means for identification of materials.

It is convenient to represent the complex permittivity of a material as $\epsilon^*=\epsilon'-j\epsilon''$, where ϵ' is the real part and ϵ'' is the imaginary part of the complex permittivity. The real part is the dielectric constant of the material ($\epsilon'=\epsilon$); whereas, the imaginary part ($\epsilon''=\sigma/\omega$ where σ=conductivity and ω= angular frequency of the electric field) describes the power dissipation in the material (loss). The dielectric spectrum of a material is a representation of its complex permittivity, expressed as a function of frequency. The dielectric spectrum provides a unique signature of a material in a particular state.

Classical dielectrometry extracts information about the state of a material construct from its dielectric

spectrum. The application of a sinusoidally varying potential of complex magnitude V and angular frequency $\omega = 2\pi f$ results in the flow of a terminal current with complex amplitude I, whose magnitude and phase is dependent on the complex permittivity ϵ^* of the material.

A capacitive sensor 100 in one preferred embodiment is an interdigitated electrode dielectrometer (IDED) sensor 102 such as presented by Melcher et al. in U.S. patent 4,814,690, "Apparatus and Methods For Measuring Permittivity in Materials. The IDED 102 utilizes a pair of interdigitated electrodes 104 and 106 to produce a spatially periodic electric field. A typical arrangement of such electrodes is shown in Figure 10A.

The electrodes are adjacent to the material of interest with an insulating substrate and a ground plane on the other side of the substrate. One of the two electrodes, 104, is driven with a sinusoidally varying voltage, v_D, while the other, 106, is connected to a high-impedance buffer used to measure the magnitude and phase of the floating potential, v_S. The periodicity of the electrode structure is denoted by the spatial wavelength $\lambda = 2p/k$, where k is called the wavenumber.

A plan view of the IDED sensor is seen in Figure 10B. The driven electrode, an excitation electrode 104, has a plurality of fingers 108. The other electrode 106, the electrode connected to the high-impedance buffer and referred to as a sensing electrode, has a plurality of fingers 110. The fingers of the two electrodes are interdigitated on the sensor face, such that fingers of the first electrode and the second electrode alternate across the sensor face.

One inherent benefit of the IDED structure is that the coupling of the applied field into the medium can be

achieved from a single surface. Dielectric measurements of thin films, for example, can be performed without having to deposit a metal electrode to the exposed side of the sample.

The depth of sensitivity of the sensor is determined by the electrode spacing. The electric scalar potential in the dielectric above the sensor in Figure 10A obeys Laplace's equation and in a Cartesian geometry with a linear lossy dielectric the solutions are of the form:

$$\Phi = \Phi_0 e^{-kx} \, [A \sin ky + B \cos ky]$$

This indicates a general property of solutions to Laplace's equation: if the excitation is periodic in space, the potential decays in the perpendicular direction with a penetration depth into the unknown dielectric equal to the spatial wavelength of the spatially periodic excitation.

An IDED is sensitive to material within a distance (from the electrode plane) of up to one third to one half of the spacing between electrodes. Sensors with different electrode spacing will consequently be sensitive to different depths into the material under test, even when operated at the same excitation frequencies as illustrated in Figures 11A and 11B. For heterogeneous media, spatial profiles of dielectric properties can be determined using multiple wavelength sensors, as each wavelength has a unique penetration depth into the heterogeneous dielectric.

The magnitude and phase of the measured signal from an IDED sensor depend on the sensor geometry and the dielectric properties of the materials in proximity to the sensor. The sensor geometry and the dielectric properties of the materials determine the complex admittance of the

sensor, i.e., the ratio between the current and the voltage between the two electrodes.

Figure 11C illustrates an IDED sensor 112 with an array design. The sensing electrode 116 is formed of a multiple of elements 118. Individual elements can be selected to locate the position of the underground object.

The admittance can be calculated from the complex surface capacitance density C, defined as $C = \epsilon^* E_x/\Phi$, where E_x is the electric field in the x direction. The spatially periodic potential Φ is derived from the voltage between the electrodes. The current in the sensing electrode can be determined by integrating the quantity $\epsilon^* E$ over the area of the electrode. Therefore all the information about the material structure is contained in the surface capacitance density.

When a single uniform layer whose thickness is much greater than the electrode wavelength is present, C can be derived by solving Maxwell's equations in the electroquasistatic case to be $C=e^*k$, where k is the spatial periodicity wavenumber.

When more than one layer is present, such as when an air gap exists between the sensor and the soil surface, the surface capacitance density at the electrode surface is calculated by sequentially deriving C at all material interfaces, beginning with the topmost layer as illustrated in Figure 12. For every layer, if C is known at the upper surface, it may be calculated for the lower surface (also from Maxwell's equations) as a function of e^* and thickness, d, of that layer. Using this approach, the air layer between the sensor and the soil surface is taken into account.

The multiple-wavelength approach to property profiling uses IDEDs with different spatial wavelengths to measure

complex permittivity variations with depth at a particular location on the component surface. Each sensor element of the multiple-wavelength IDED produces a measurement which corresponds to a depth of material that is proportional to the wavelength of that particular element. The element with the shortest wavelength will respond to the dielectric properties of the material closest to the surface, whereas the longer-wavelength elements will be sensitive to the material below that as well. Thus, the complex permittivity profile of the material can be determined from measurements made with multiple-wavelength IDEDs. This is described in further detail in U.S. Patent No. 4,814,690 titled "Apparatus and Methods for Measuring Permittivity in Materials" which issued on March 21, 1989, the entire contents of which are incorporated herein by reference.

The ability to independently vary the applied frequency and the spatial wavelength of the electrodes allows one to measure both the temporal and the spatial frequency response of the material. The temporal response, or dielectric spectrum, is obtained by varying the excitation frequency, and the spatial response is obtained by varying the spatial wavelength of the sensor. Because the temporal (ω) and spatial (k) domains are independent, this technique has been referred to as the 'imposed ω-k' approach to dielectrometry.

One of the features that differentiates this approach from classical techniques utilizing single wavelength structures is the fact that the heterogeneity of the material under test can be deduced independently from the temporal frequency response. This can be achieved by performing variable spatial wavelength measurements at the same temporal frequency. The spatial distribution of the dielectric properties can thus be determined without making

assumptions about the nature of the material. This additional freedom allows an unconstrained evaluation of the physical mechanisms that govern the dispersive nature of the dielectric properties.

Quasistatic indicates that the frequency of excitation is sufficiently small such that the propagation of electro-magnetic radiation over the area of interest is approximately instantaneous and therefore approximately obeys a simplified version of Maxwell's Equations in which either electric or magnetic fields are of primary interest. In the case of this sensor it is the electric fields which are of primary interest and it is the coupling of electrodes through these electric fields which is termed capacitance. Since the sensor uses this coupling to probe for materials of varying dielectric properties such as landmines, the term capacitive has been used to describe the sensor.

An alternative embodiment to the interdigitated electrode dielectrometer (IDED) sensor is a sensor that has a single sensing electrode, or a single location for a sensing electrode, and excites only one period of the electric field. This design is more appropriate for non-portable sensors. A multiple wavelength (periodic) version of this sensor could be used for vehicle mounted applications.

The basic single sensing electrode sensor 120 design as illustrated in Figure 13 consists of two excitation electrodes 122, a sensing electrode 124, a guard electrode 126 and a shielding plane 128.

The excitation electrodes 122 are driven by a high voltage source which is typically sinusoidal (500V peak in experiments). Electric field lines emanate from the excitation electrodes and fringe through the half-space

above and below the face of the sensor, terminating on the shielding plane 128, guarding electrode 126 and sensing electrode 124. In the preferred approach, the primary sensing electrode 124 is held at a voltage potential equivalent to that of the shield and guard, which is typically a ground reference, while the current required to maintain this sensing electrode voltage is measured. Alternatively, the sensing electrode could be allowed to float, its voltage being detected. Keeping both the sense electrode and shield/guard electrodes at identical voltages effectively eliminates the capacitive coupling between these electrodes. Such coupling can result in signal attenuation and sensitivity loss, since it is the coupling between the sense electrode and excitation electrodes that is of interest.

The ratio of excitation voltage to the current flowing to and from the sensing electrode, also known as the transimpedance, is then used as the sensor output. The output is compared with the response from both finite element and analytical models of the sensor and its surroundings to determine material or geometric properties of the surroundings. The output during scanning is compared with the output with no buried objects present when used to detect changes in the surroundings over position or time.

The overall structure is driven by the desire to induce dielectric polarization in materials which are not locatable directly between electrodes, but rather materials which are in a half-space region separated from all electrodes in the adjacent half-space. In order to accomplish this, fringing electric fields are setup by electrodes held at two different voltage potentials and placed in the plane separating half-spaces. The use of two

excitation electrodes at the same potential adds a degree of symmetry to the fields, while placing the sensing electrode at the center eliminates disturbances from unwanted interference as a result of the protection from the shielding plane. The use of a single excitation electrode permits deeper sensor penetration with the same size footprint. In terms of electric field distribution, the sensing electrode and guard shield can be viewed as a single electrode since they are at the same voltage potential. The spatial distribution of the fringing fields is then primarily determined by the excitation electrode and sense/guard shield electrode size and position in the plane of the sensor face.

From closed form 2-D Laplacian solutions for electric fields with periodic boundary conditions it is known that the electric field intensity will decay into the half-space possibly containing the landmine. It is also known that boundary conditions on potential having lower spatial frequencies will result in a slower rate of decay of electric field intensity with distance from the electrode plane. This fact is utilized in the aperiodic structure by separating excitation and guard/sense electrodes until practical sensor size limitations are reached, thereby increasing the low frequency spatial spectral content of the boundary potential at the sensor's face. The gap between electrodes and electrode widths have been chosen so that the potential at the boundary approximates that of a single period of a sinusoid in order to minimize higher spatial harmonics which will cause an undesirably faster decay of the relative electric field intensity. Placing the shield plane too close to the face of the sensor also tends to create higher order harmonics and is therefore placed as far as practical from the sensor face. All of

these efforts are aimed at increasing the relative electric field intensity as deep as possible into the half-space being probed. However, having sufficient field intensity at a desired probing depth into the half-space is necessary but not sufficient in being sensitive to the materials located there. Further attention must be given to the design of the sense electrode and guard.

Referring to Figure 14, the electric field distribution of an dielectrometer sensor illustrates several factors which the placement of elements increase sensitivity. Electric fields exist in both the half-space being probed and the region between the guard/sensor and the shield plane. The electric field lines between the guard/sensor and the shield plane primarily terminate on the side of the guard electrode opposite the half-space being probed. The termination of these field lines contribute to the total current flowing to and from the guard/sense electrode; however, this portion of the current is insensitive to the region being probed. The placing of the guard electrode parallel to the sense electrode and opposite the region being probed eliminates the current flow to the sense electrode on the side between the sensor face and the shield plane, resulting in a greater sensitivity of the current to the region being probed.

Still referring to Figure 14, it can be seen that field lines with the shallowest penetration terminate on the outer edges of the guard/sense electrodes, while field lines with the deepest penetration terminate in the middle of the electrodes. It should also be noted that the density of field lines terminating on the electrode tends to decrease with increasing depth of penetration. This is due to the fact that the electric fields inherently decay with distance from their charge sources. As a result, the

sensitivity of the measured current flowing in and out of the sense electrode is inherently biased toward near properties rather than deep properties. In order to counter this effect the sense electrode has been reduced in width so that only deep penetrating field lines terminate on it, increasing the sensitivity of the measured current to deep effects. The guard electrode replaces the parts of the sense electrode, which were reduced in order to maintain the low spatial spectral frequency components.

Additional imaging capability may also be achieved by further breaking the original single sensing electrode 124 in separate parts as shown in Figure 15A, giving further information about depth of objects in the half-space being probed. This sensor 120 utilizes a single column of a plurality of sensing side-by-side elements 132. In preferred embodiments, there are three or five elements. As can be seen from Figure 14, the center sensing electrode of Figure 15A senses the longest and deepest spatial half wavelengths, while end electrodes sense shorter, shallower half wavelengths.

Breaking the sensing electrode up into separate elements along what has been the depth of the cross-section as depicted in Figure 15B, allows for imaging of the half-space being probed. This sensor 120 utilizes a single row of four sensing elements 134 surrounded by the guard electrode 126. A pair of drive electrodes are located on either side. The four sensing electrodes can be connected differently such that three outputs are produced which are proportional to differences in adjacent electrodes. In a preferred embodiment numerous (e.g. 20 sensing elements will be used in a row to increase image resolution). Without the side sensing elements of the previous embodiments, this sensor does not include air gap

compensation capability. When the output of each element is directly used as information in building an image, results similar to scanning a single element will be obtained. The array of elements excels when utilized with additional circuitry, which differences the measurements from adjacent or alternating elements. Differencing the elements allows for additional sensitivity to small, but spatially abrupt (with respect to the spacing of the elements being differenced) changes in the dielectric properties in the half-space, as is the case when searching for objects such as landmines. With the sensor stationary a one-dimensional image is formed by numerically integrating the measured differences after their conversion from analog signals to digital values. By scanning the array in a direction perpendicular to the line of array elements two-dimensional images may be formed by combining the one-dimensional image at each position of the scan. Here incorporating an absolute measurement (i.e., not differential) of one or more of the elements at each scan position can be useful in accounting for variations in the sensor lift-off when scanning over a surface. Additional information from electrodes sensitive to properties at various depths as described in the previous section may also be incorporated for improved object discrimination and three-dimensional imaging. A full two dimensional array combining the features of Figures 15A and 15B may also be provided.

Figure 15C illustrates an alternative embodiment to the sensor of Figure 15A. The sensor has a guard electrode 126 which surrounds the side-by-side elements 132 on the same plane. A separate guard plate 140 overlies, underlies as seen in Figure 15C, the sensing electrode and the guard

electrode. The guard plate is electrically connected to the guard electrode.

The input-stage of a circuit for measuring the current flowing in and out of the sense electrode, while maintaining a virtual ground potential, is shown in Figure 16. It includes an electrometer grade operational amplifier in a current integration configuration. The current integration configuration is preferred over the common transimpedance amplifier consisting of a resistor in the feedback loop rather than a capacitor. This is primarily due to the relatively small current being measured and the relatively large resistor which would be required. The resistor in the feedback loop serves only to bleed charge off of the integration capacitor to avoid saturation from static electric fields and amplifier bias currents. The RC time constant of R1 in parallel with C1 is set such that the break frequency is less than the excitation frequency, but the time constant is fast enough to allow a fast decay of accumulated charge from stray static fields at the sensor electrode when scanning.

In the case of an array of elements used in differential mode, each element would utilize one of the previously described circuits. The output from pairs of circuits from adjacent or alternating elements would then be fed into a common difference amplifier providing a single output for each pair of electrode.

A test of the sensor shown in Figure 15B was conducted. A land mine specimen of interest (M14) was buried to the desired depth in the sand bed. For this test a scanning mechanism for the test bed was created. The sensor data acquisition system was initiated and the scan motor was energized. The data acquisition system

automatically records the differential sensor outputs (the difference between adjacent sensing elements).

The data produced during a scan consists of an array of data points, four elements wide by about 200 elements long. In the preferred embodiment numerous (e.g. 20 or more) elements will be used and rapid scanning (e.g. 1 ft/sec.) will be provided. This data can be used to create an image by connecting data points of equal value with contour lines, as a topographic map uses contour lines to connect points of equal elevation. Intermediate values can be developed by interpolation to increase contour line density.

Figure 17A illustrates the results of a sequence of scans conducted with the inert M14 mine buried at increasing depths in the sand bed. The data shown is raw data that had not been processed to remove air gap effects. Future signal processing efforts would substantially improve the quality of mine images produced by the capacitive sensing array. In the top scan the top of the mine is at the surface of the sand. In the second scan down, the top of the mine is buried to a depth of 1 cm below the surface, and so on.

The mine can be clearly seen at up to 2 cm depth in the images produced. Not only are the sensor capacitance values significantly affected by the presence of the mine, but also the gradient from unaffected values is quite steep. It is recognized that pattern recognition techniques such as edge detection can be used to discriminate mines from clutter. This data was taken at a single frequency. Once a target is detected, multiple frequencies are used for false alarm rejection and discrimination/identification of mines. For example,

dielectric spectroscopy can permit discrimination between plastic and rocks.

Figure 21A and 21B show the dielectric constant and conductivity variations with frequency for several materials. This shows that a great deal of information is available in the quasistatic frequency range under 100 MHZ compared to the 1-10 GHz range that ground penetrating radar operates.

Tests were also conducted to evaluate system repeatability over time. Figure 17B illustrates the results of scans conducted approximately three hours apart. These scans were conducted with the M14 mine at a depth of 1 cm. Sensor and system response to the mine and the surrounding sand bed is extremely repeatable.

Several scans were conducted to show the clutter suppression capability and metallic object detection. A buried rock was seen to be readily distinguishable from the plastic M14 mine and the metallic object (a dime) was also easily detected by the capacitive sensor. Figure 17Ca illustrates the difference between the M14 mine and the rock. The rock is the area at the 47 cm mark, whereas the M14 mine is at about the 36 cm mark and on the centerline of the scan. Also, a dime was placed between the rock and the landmine. The dime was also detected. Figure 17Cb illustrates the ability of the capacitive array to detect metallic mines and UXO. The area at the 37 cm mark is an intact bomblet buried to a depth of 1 cm. As would be expected from the inclusion of a material of high dielectric constant, such as the metallic bomblet, within the sensed volume of sand, the sensor capacitance is increased. Also, the dime can be detected easily at approximately 1 cm depth using the capacitive array.

Figure 22A and 22B show the IDED responses for metal and plastic at various depths. Thus, metal and plastic can be easily differentiated. For example, if the soil dielectric constant is above that for the plastic then the metal and plastic response will go in opposite directions.

Dielectric spectroscopy can be preformed to identified material types. The types of spectroscopy that can be preformed include derivative spectroscopy, ratio spectroscopy and other common types.

Dielectrometry measurements using long wavelength IDEDs can easily discern planar plastic and metal structures below the surface of dry or wet sand, and can be used to detect land mines without ground contact. However, an alternative embodiment may be more effective in certain instances. An alternative embodiment is an electrode arrangement which utilizes a circular center electrode surrounded by a coplanar, concentric electrode, a "Bull's Eye" sensor as illustrated in Figure 16.

An axisymmetric computer simulation of the response of this sensor to a realistic nonmetallic mine was run. The mine was modeled as a 4 cm diameter cylinder, 4 cm thick, made of ABS and rubber, with two small metal components (firing pin and fuze), buried in dry sand. These dimensions and materials are representative of the Chinese Type 72 AP mine. A 2.5 cm sensor stand-off distance was used. Sensor capacitance is shown in Table 2. Wet sand further improves measurement sensitivity by providing values of conductance as well as capacitance. Since our existing computer simulation software can only solve planar geometries for AC conduction problems, the planar analog to the "Bull's Eye" geometry and cylindrical mine was simulated at 10 Hz. The calculated capacitance and conductance per unit length are listed in Table 3.

	Dry Sand	Wet Sand (10 Hz)	
Mine Depth (cm)	Capacitance (pf)	Capacitance (pf/m)	Conductance (S/m x 10^{-14})
0	5.276	19.4	1.51
2.5	5.363	21.4	2.18
5.0	5.386	21.4	2.03
7.5	5.395	21.3	1.95
10	5.398	21.3	1.91
No Mine	5.401	21.3	1.83

Table 2. Computed "Bull's Eye" Sensor Response to Buried Nonmetallic Mines in Dry and Wet Sand.

This preliminary analysis of the "Bull's Eye" electrode arrangement indicates fair capacitance response to nonmetallic mines close to the surface in dry sand, but poor response at increasing burial depths. In wet sand, however, the sensor conductance remains sensitive to the mine's presence down to 10 cm depth, as was seen in the planar layer analysis of lossy soil in the previous section. The lossy soil has a substantial ϵ'' as defined earlier.

Combined MWM and Dielectrometer Approach

Both the MWM and the dielectrometer sensors individually can detect and characterized land mines and bomblets that existing technology could not detect or, if detected, could not characterized. However, the results of both sensors produces details that were not possible individually. Table 3 shows the characteristics of both.

		Mine Constituents				Placement	
Sensor type	Potential attribute	high ferrite metals	low ferrite metals	non-ferrous metals	plastic (low or no-metal)	soil (clay, loam, etc.)	sand
MWM	detection	✓	✓	✓		✓	✓
	depth	✓	✓	✓		✓	✓
	shape	✓	✓	✓		✓	✓
	identification	✓	✓	✓		✓	✓
IDED	detection	✓	✓	✓	✓	✓	✓
	depth	✓	✓	✓	✓	✓	✓
	shape	✓	✓	✓	✓	✓	✓
	identification				✓	✓	✓

Table 3. Summary of the materials and characteristics for MWM and IDED.

The MWM comprises a meandering primary winding, with a secondary winding on each side of the primary. The MWM is essentially a planar transformer, in which the primary winding is inductively coupled with the secondary winding through the neighboring material. The IDED, on the other hand, consists of two separate, but coplanar, electrodes. Whereas the MWM can be considered a transformer within a single plane, the IDED can be considered a parallel plate capacitor within a single plane.

While no single tool will detect and identify all subsurface objects, the MWM (or single period deep penetration array) and the IDED (or improved single period design described earlier) sensors will located and identify a majority of mines and bomblets for humanitarian demining problems.

In one embodiment the deep penetration MWM-Array might be used to detect metal, then the single period

dielectrometer might be used to determine if the metal is surrounded by plastic.

It is recognized that the MWM-Array system and the IDED-Array system can have features that can be used to augment the work of various other tools. For example, to support the use of an airknife for bomblet removal following a detection, the MWM-Array Bomblet Discrimination System could include a means of marking the exact bomblet location. Once a bomblet has been identified, the sensor array could be maneuvered to position the bomblet to a particular part of the array, for example the center. The system would be equipped with a means of dispensing spray paint or another environmentally friendly marker directly to the exact bomblet location.

While the sensors discussed above have been individual sensors, it is recognized that a Local Positioning System (LPS) could be used to coordinate large area scanning by teams of field operators and to map and record buried ordinance and clutter locations. In view of the relative lightweight of the sensors, a light-weight mat array could cover large arrays, several hundreds of feet, without exploding encountered landmines, such as illustrated in Figure 19A and 19B. The light-weight mat has a flexible sheet, such as a durable flexible fabric or composite material, that retains the conductors in proper position.

It is recognized that the wavelength can be varied by placing the electrodes on an adjustable face plate as illustrated in Figure 20. Both the driven electrodes and the sensing electrodes are attached to an accordion or scissors frame, which can expand and contract. The moving of the driven electrodes and the sensing electrodes closer or further apart results in mechanically varying the wavelength.

EQUIVALENTS

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. Those skilled in the art will recognize or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described specifically herein. Such equivalents are intended to be encompassed in the scope of the claims.

CLAIMS

What is claimed is:

1. An apparatus for detecting electromagnetic properties comprising:

a primary winding having a series of parallel, spaced linear conductor sets for receiving a current, the primary winding having at least one conductor associated with each parallel conductor set and having a varying number of conductors associated with each parallel conductor set to shape a spatial magnetic waveform generated by the primary winding; and

an electromagnetic sensor for sensing a resulting electromagnetic response.

2. The apparatus of claim 1 wherein the waveform is a periodic sinusoid.

3. The apparatus of claim 1 wherein the waveform is one period of a sinusoid.

4. The apparatus of claim 2 wherein the sensor comprises an array of secondary windings, wherein at least one of the secondary windings is located between parallel conductors of each pair of adjacent parallel conductor sets of the primary winding.

5. The apparatus of claim 4 wherein the plurality of secondary windings are distributed in two dimensions.

6. The apparatus of claim 4 further comprising a second secondary array and a second primary winding which are oriented perpendicular to the conductors of the first primary winding.

7. The apparatus of claim 1 wherein the linear conductors on one side of a center line have current flow in one direction and the linear conductors on the other side of the center line have current flow in the opposite direction.

8. The apparatus of claim 7 wherein the sensor comprises an array of secondary windings, wherein at least one of the secondary windings is located between parallel conductor sets of each pair of adjacent parallel conductor sets of the primary winding.

9. A method of detecting an object containing metal located below the surface of the ground comprising the following steps:

disposing a plurality of parallel, spaced linear conductor elements in proximity to the ground;

through the conductor elements imposing an electromagnetic field in the ground with a dominant spatial wavelength; and

sensing a resulting electromagnetic response of the object in the ground to the imposed magnetic field.

10. The method of claim 9 wherein all primary elements carry current in the same direction and the number of wires is the same in each conductor set so that the spatial wavelength is essentially infinite.

11. The method of claim 9 wherein the step of sensing is performed by a sensor coil array.

12. The method of claim 9 wherein the electromagnetic response is sensed by a sensor coil array of elements disposed parallel to the electromagnet elements imposing the magnetic field.

13. The method of claim 9 wherein each of the conductor elements imposing the magnetic field has at least one individual conductor associated with each parallel conductor set and a varying number of conductors are associated with the parallel conductor sets to shape an electromagnetic waveform imposed in the ground.

14. The method of claim 13 wherein the electromagnetic element capable of sensing a magnetic field is an array of secondary windings, wherein one of the secondary windings is located between parallel conductor sets of each pair of adjacent parallel conductor sets of the primary winding.

15. The method of claim 14 further comprising the step of translating electromagnetic response of the secondary windings into estimates of one or more properties of the object based on a modeled response to the spatial waveform.

16. The method of claim 15 further comprising providing a second sensor array which is perpendicular to the parallel conductors of the first primary winding.

17. The method of claim 16 further comprising providing a second primary winding perpendicular to the first primary winding.

18. An apparatus for detecting objects containing metal located below the surface of the ground, the apparatus comprising:

a plurality of parallel, spaced linear conductor sets capable of imposing an electromagnetic field with a dominant spatial wavelength in the ground, the dominant spatial wavelength having a length of at least 12 inches;

a signal source which applies an electromagnetic signal to the conductor sets to impose an electromagnetic field in the ground; and

sensor elements to sense the resulting electromagnetic response of the objects in the ground to the imposed electromagnetic field.

19. The apparatus of claim 18 further comprising a rigid conductor element support structure adapted to be scanned across the surface of the ground.

20. The apparatus of claim 18 further comprising a flexible sheet to contain the conductors.

21. The apparatus of claim 19 wherein the conductor elements are distributed so as to approximate a sinusoidal distribution for the imposed magnetic field.

22. The apparatus of claim 19 wherein the conductor elements comprise a drive coil array and at least one sensor coil array.

23. The apparatus of claim 18 wherein each of the conductor sets imposing the magnetic field has at least one conductor and varying numbers of conductors are associated with parallel conductor sets to shape an electromagnetic waveform imposed in the ground, with each individual conductor in each conductor set being electrically insulated from the other parallel conductors.

24. A dielectrometer apparatus comprising:

a sensor face;

an excitation electrode carried on the sensor face and driven with a varying voltage;

a sensing electrode carried by the sensor face; and

a guard electrode on the sensor face surrounding the sensing electrode, the guard electrode being at about the same voltage as the sensing electrode.

25. The apparatus of claim 24 further comprising

a shielding plane behind and spaced from the sensor face, the shielding plane for blocking unwanted interference.

26. The apparatus of claim 25 further comprising a guard plate interposed between the shielding plane and the guard electrode.

27. The apparatus of claim 26 wherein the sensing electrode has a plurality of elements in a column at different distances from the excitation electrode.

28. The apparatus of claim 26 wherein the sensing electrode has a plurality of elements in a row wherein each element is equidistant to the excitation electrodes.

29. The apparatus of claim 28 wherein the elements are connected such that differences in measurements between adjacent elements can be used to detect small spatially abrupt changes in the dielectric properties.

30. The apparatus of claim 25 further comprising a high-impedance buffer connected to the sensing electrode to measure the magnitude and phase of the floating potential.

31. A method of detecting an object located below the surface of the ground comprising the following steps:

providing a dielectric sensor having a first electrode and a second electrode;

driving the first electrode with a varying electromagnetic signal to establish a varying electric field through the ground to the second electrode; and

measuring the magnitude and phase of the potential of the second electrode.

32. The method of claim 31 wherein the first electrode has a plurality of fingers and the second electrode has a plurality of fingers, and the fingers of the electrodes are interdigitated on a sensor face, such

that finger of the first electrode and the second electrode alternate across the sensor face.

33. The method of claim 31 wherein the first electrode is an excitation electrode having a pair of excitation electrodes carried by a sensor face and the second electrode is a sensing electrode carried by the sensor face and interposed between the excitation electrodes; and further comprising

a guard electrode surrounding the sensor electrode at the sensor face and which is at about the same voltage as the sensing electrode.

34. The method of claim 33 wherein the sensing electrode has a plurality of elements in a column at different distances to the excitation electrode.

35. The method of claim 33 wherein the sensing electrodes closer to the excitation electrodes measure stand-off distance and the sensing electrodes farther from the excitation electrodes detect buried objects.

36. The method of claim 33 wherein the sensing electrode has a plurality of elements in a row wherein each element is equidistant to the excitation electrodes and the elements are connected such that differences in measurements between adjacent elements can be used to detect small spatially abrupt changes in the dielectric properties.

37. The method of claim 33 wherein the sensing electrode has a plurality of elements in a row wherein each element is equidistant to the excitation electrodes

and the elements are individually monitored to measure absolute properties.

38. The method of claim 33 wherein the voltage is varied sinusoidally and further comprising the step of connecting the second electrode to a high-impedance buffer.

39. The apparatus of claim 28 further comprising the step of performing dielectric spectroscopy to identify material types.

40. The method of claim 31 further comprising the steps of:

disposing electromagnetic elements in proximity to the ground;

through the electromagnetic elements imposing a magnetic field in the ground with a dominant spatial wavelength; and

sensing a resulting electromagnetic response of the object in the ground to the imposed magnetic field.

41. The method of claim 40 wherein the electromagnetic element capable of imposing a magnetic field is a primary winding having a series of parallel spaced conductors and has at least one conductor associated with each parallel conductor set and has a varying number of conductors associated with each parallel conductor set to shape an electromagnetic waveform imposed in the ground.

42. An apparatus for detecting an object locate below the surface of the ground, the apparatus comprising:

a sensor face having an area of at least a square foot;

a first electrode carried by the sensor face driven with a sinusoidally varying voltage; and

a second electrode carried by the sensor face, the sinusoidally varying voltage establishing an electric field having a spatial waveform determined by the distance between the first and second excitation electrodes; and

a circuit for sensing the voltage response of the second electrode.

43. The apparatus of claim 42 further comprising a high-impedance buffer connected to the second electrode to measure the magnitude and phase of the floating potential.

44. The apparatus of claim 42 wherein the waveform is one half period of a sine wave.

45. The apparatus of claim 42 wherein the waveform is one period of a sine wave.

46. The apparatus of claim 42 wherein the waveform is multiple periods of a sine wave.

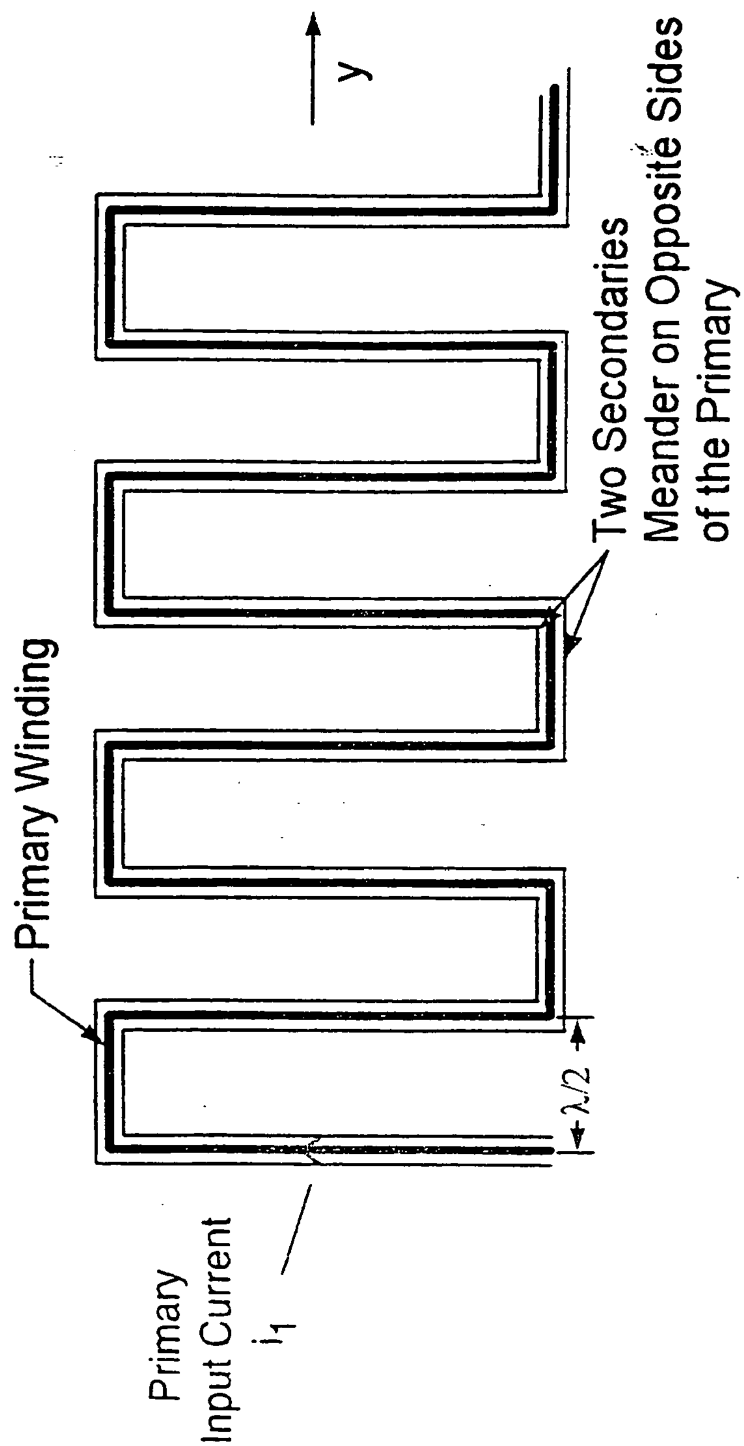
y
Two Secondaries
Meander on Opposite Sides
of the Primary
Primary Winding
λ/2
Primary
Input Current
i_1

Figure 1

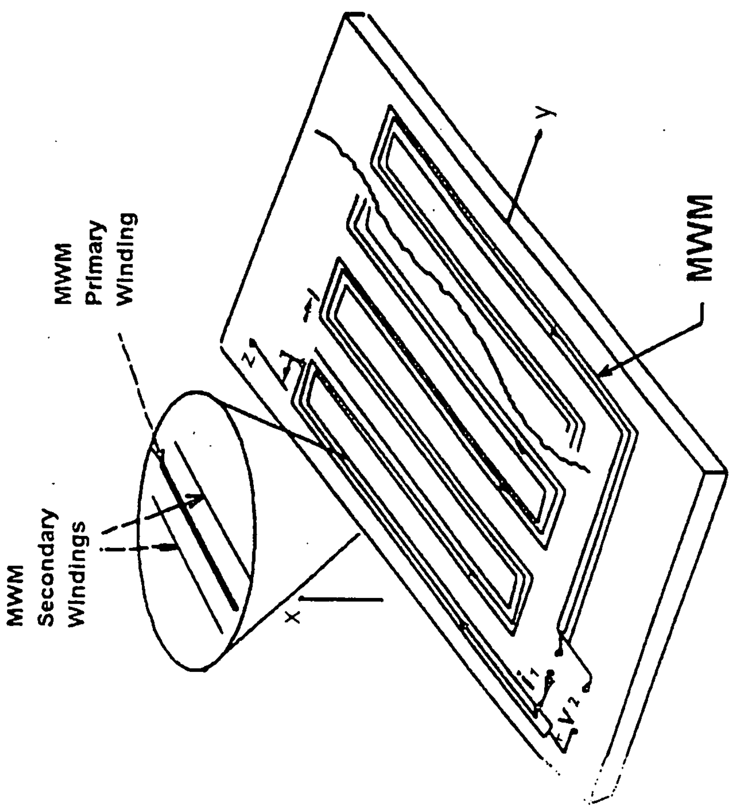

Figure 2A

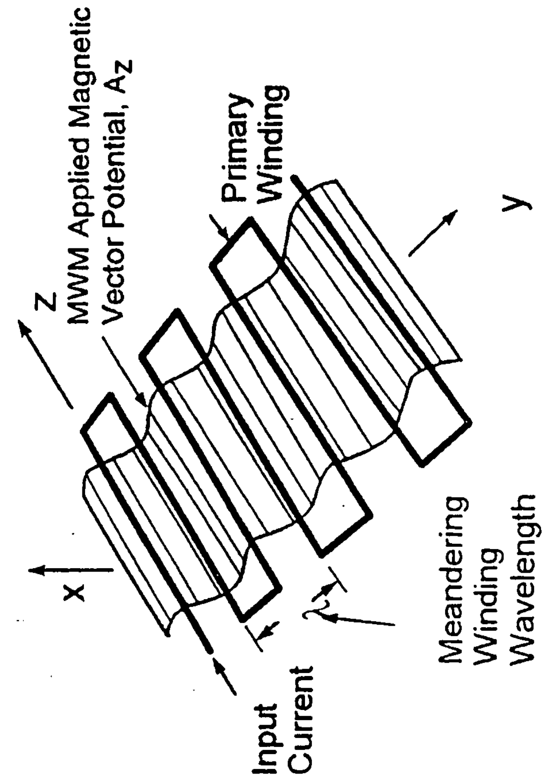

Figure 2B

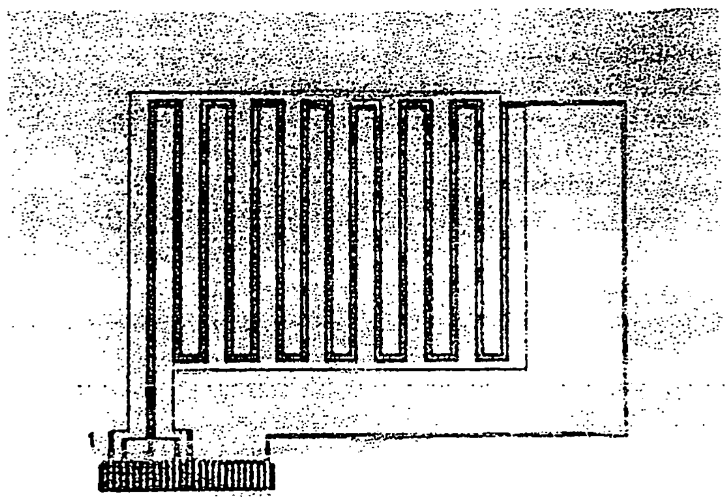

Figure 3

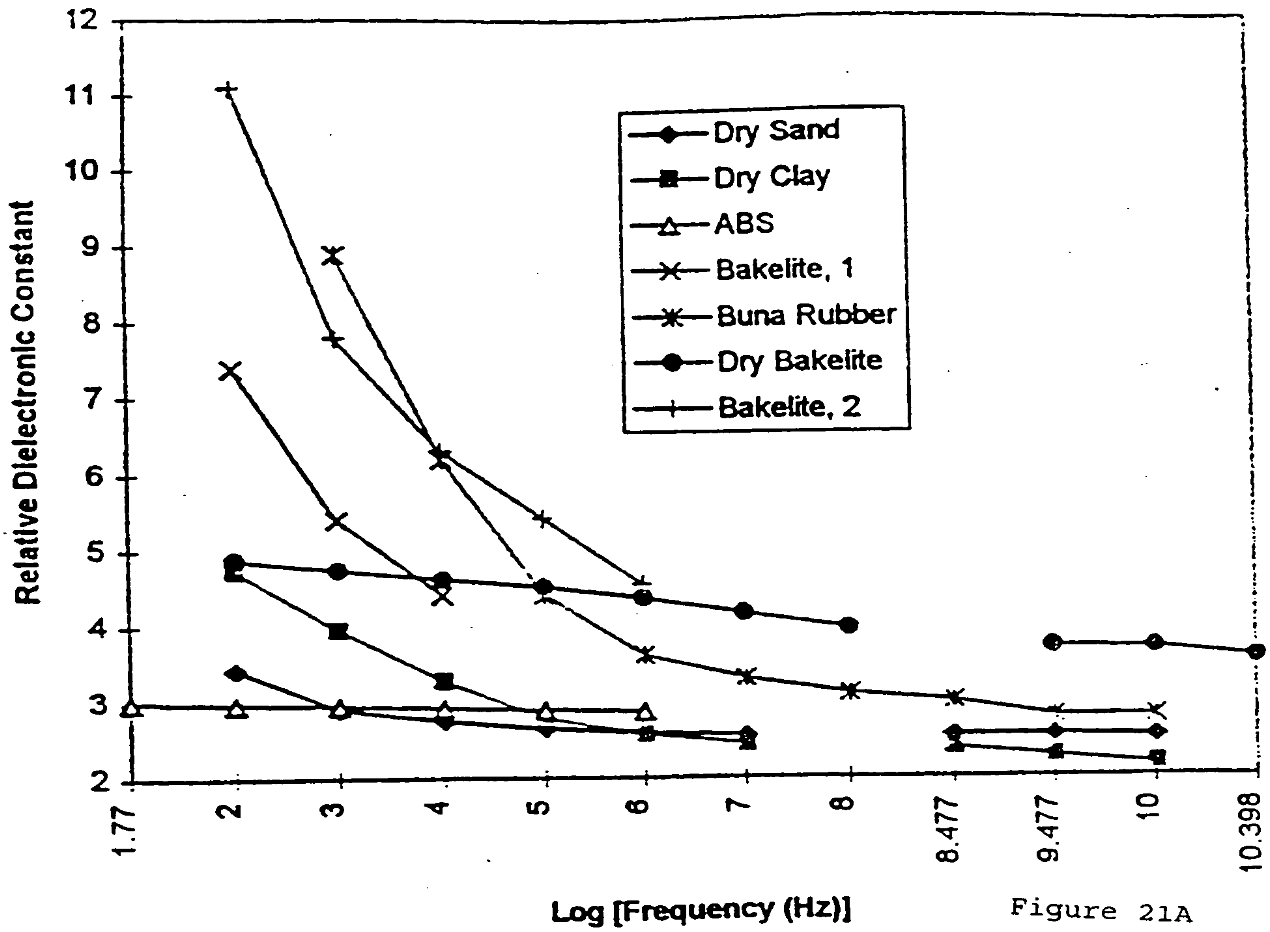

Figure 21A

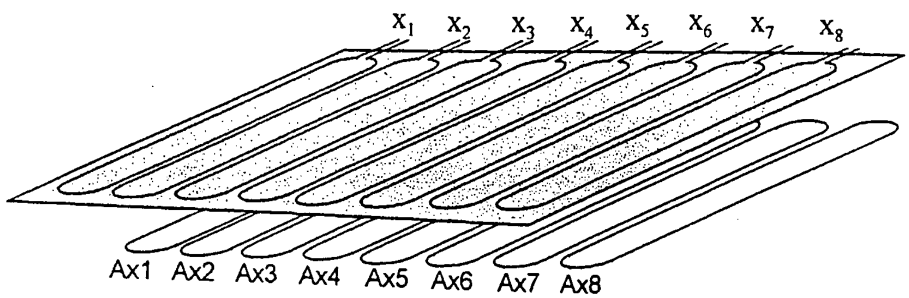

Figure 4

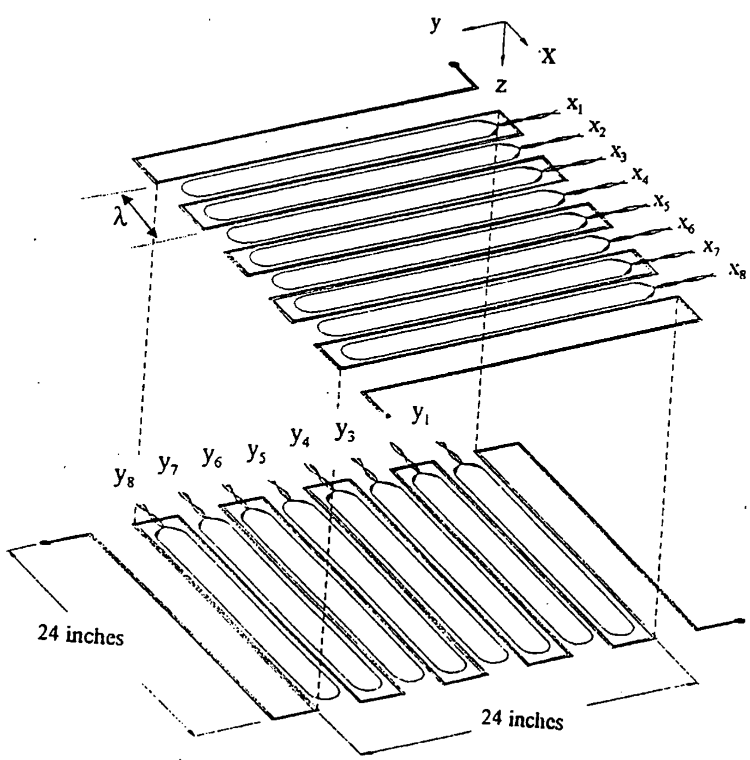

Figure 5

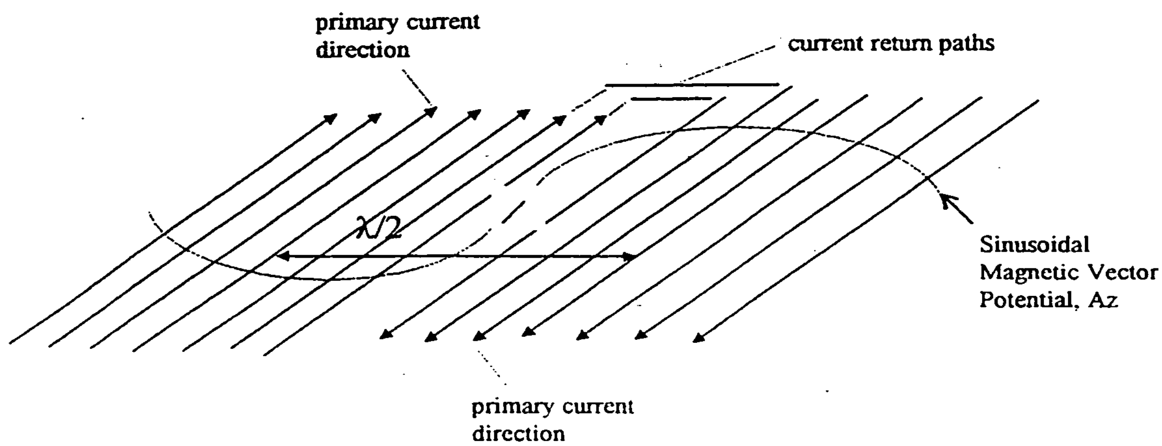

Figure 6A

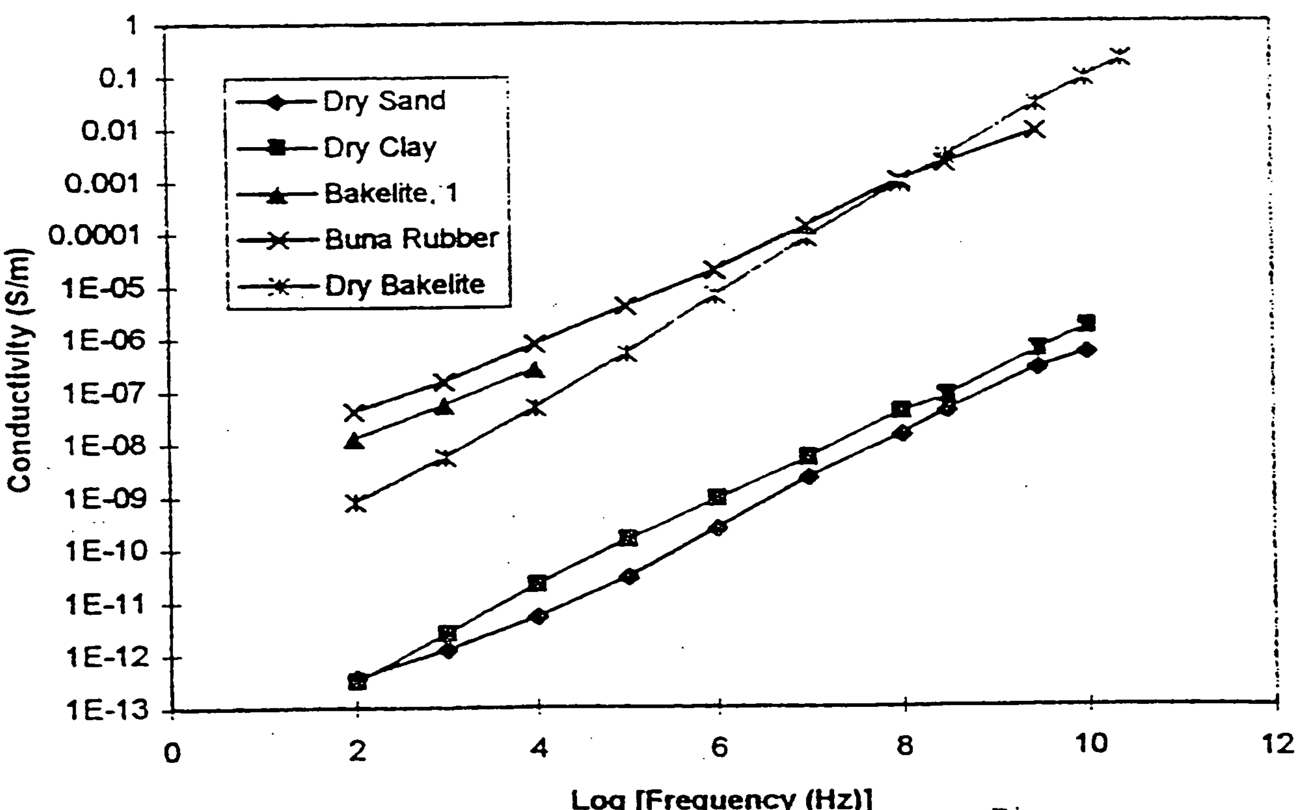

Figure 21B

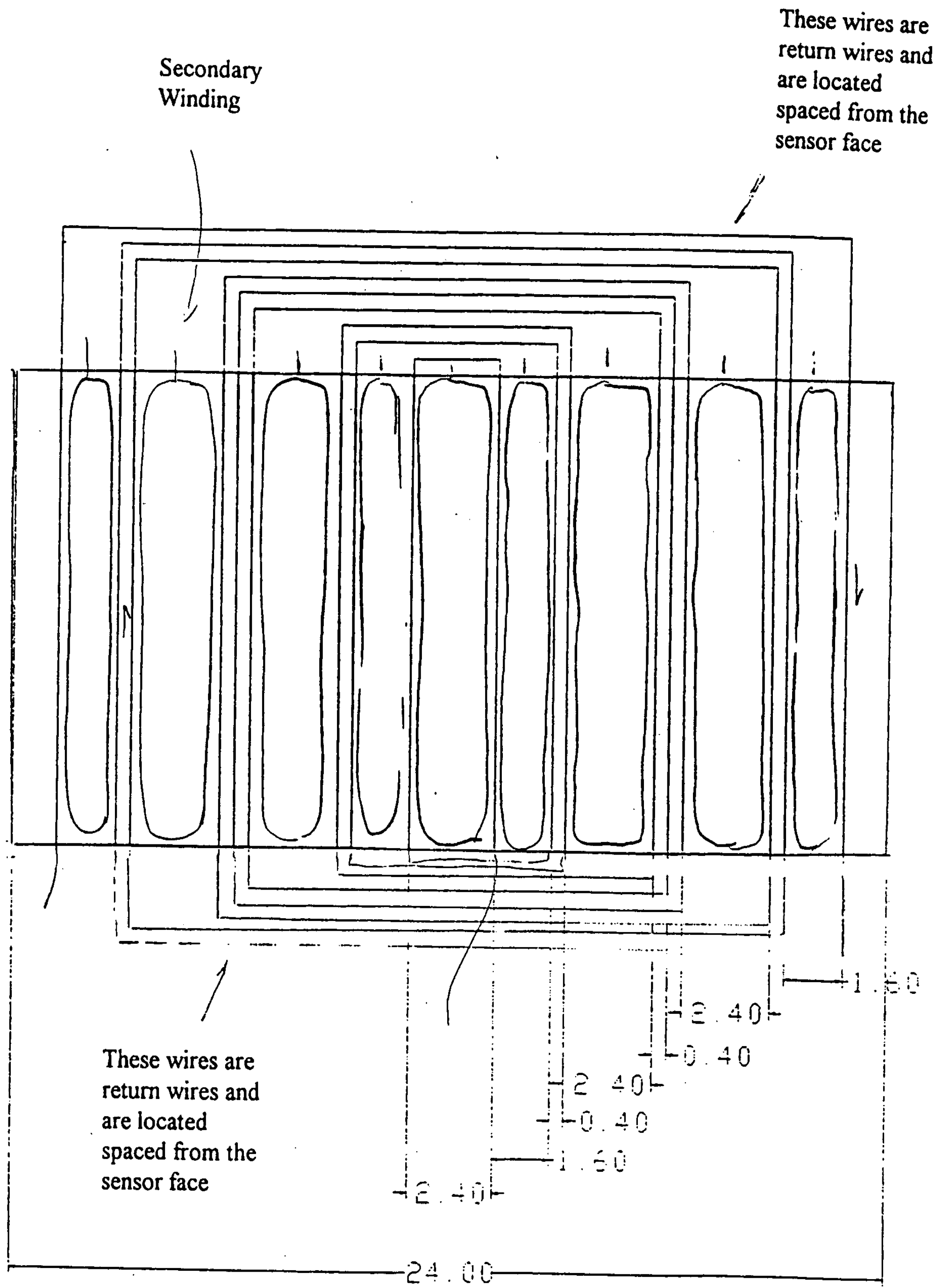
Secondary Winding
These wires are return wires and are located spaced from the sensor face
These wires are return wires and are located spaced from the sensor face
1.60
2.40
0.40
2.40
0.40
1.60
2.40
24.00

Figure 6B

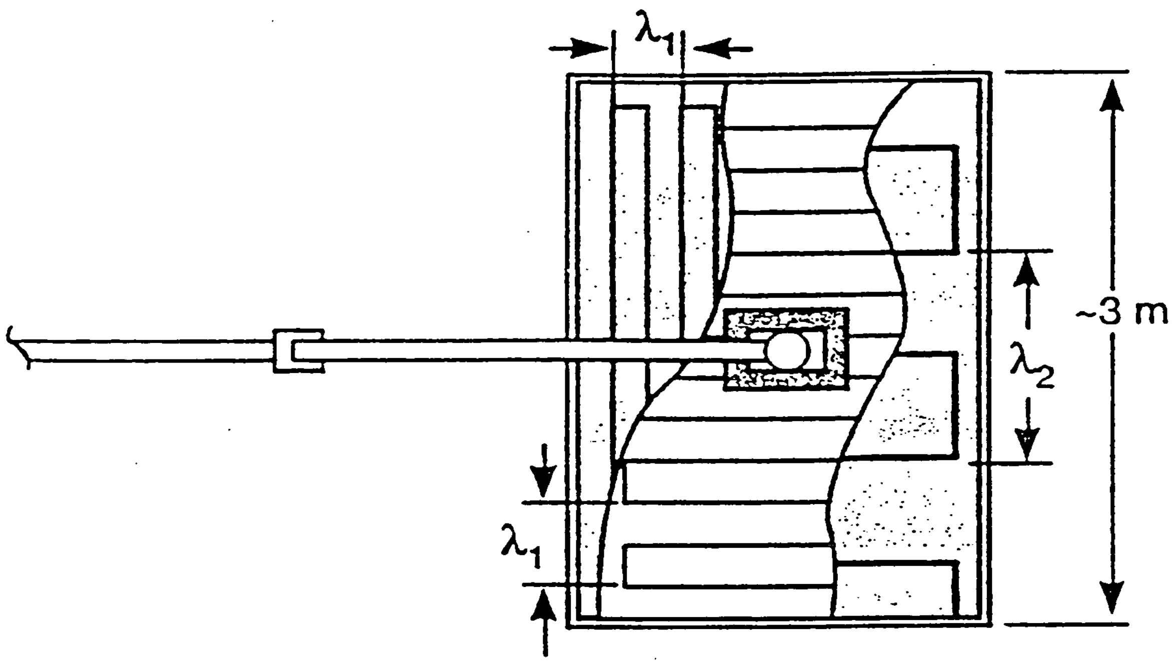

Figure 7A

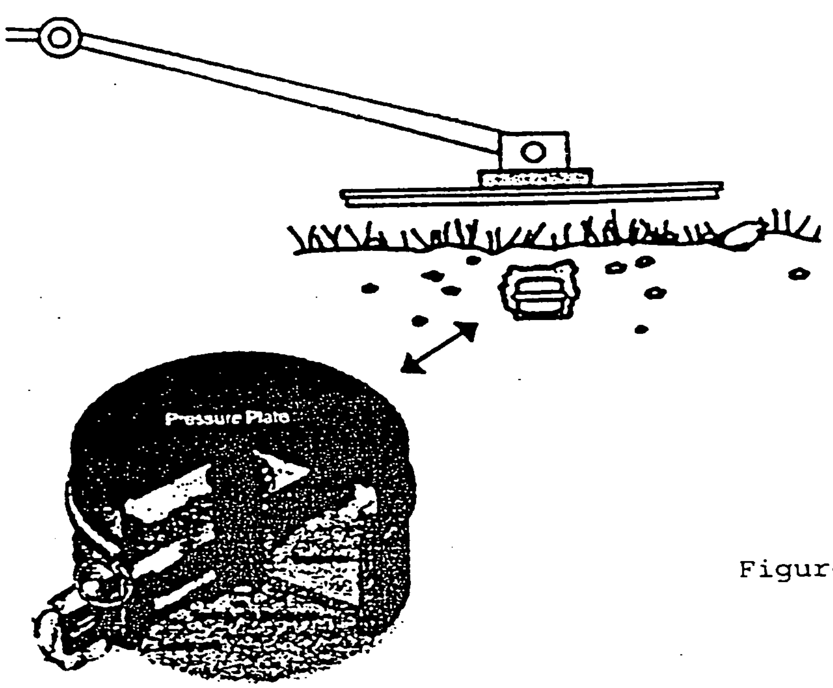

Figure 7B

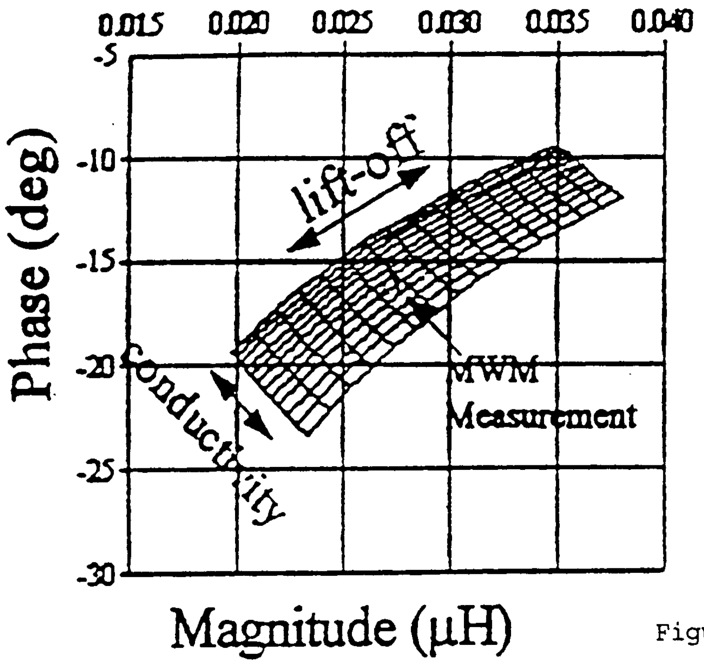

Figure 9A

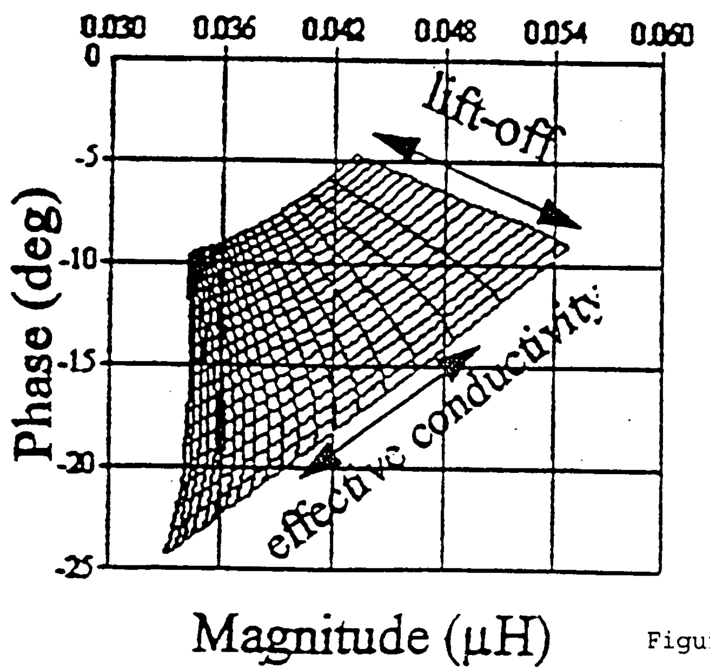

Figure 9B

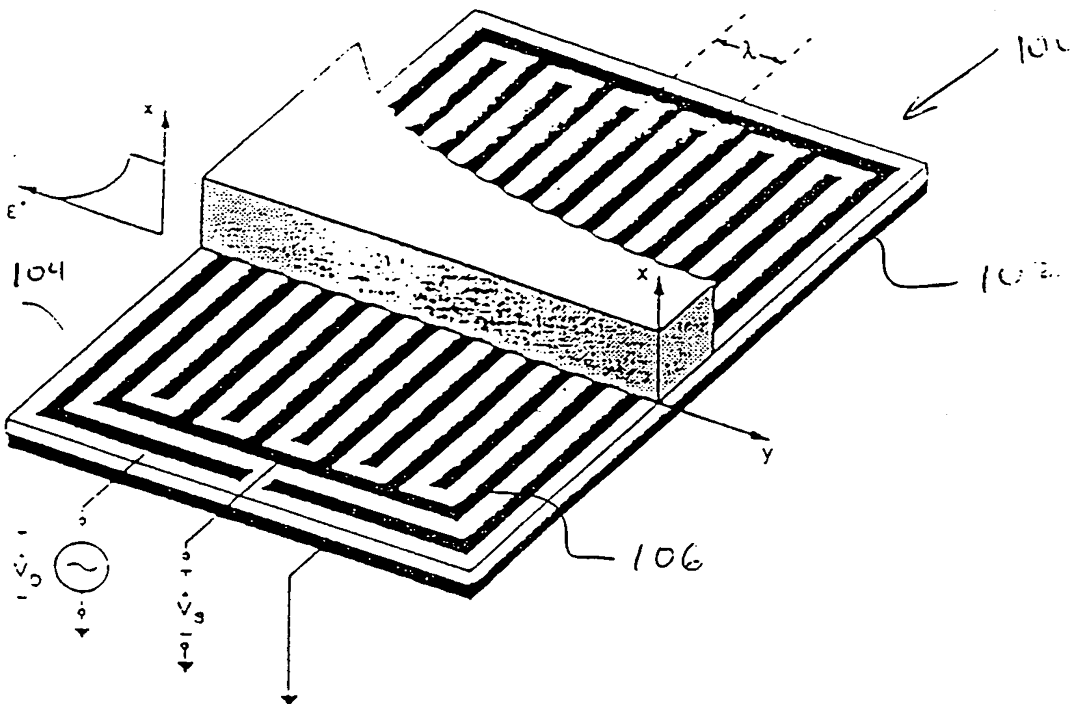

Figure 10A

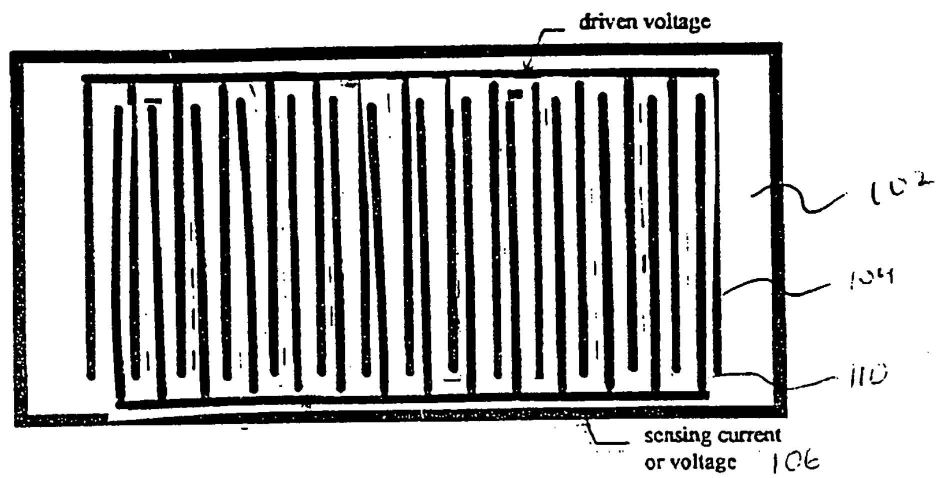

Figure 10B

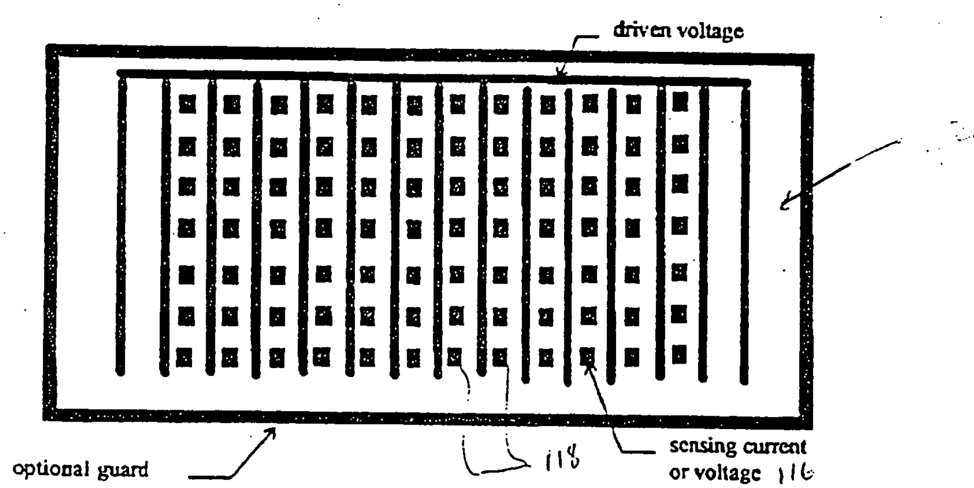

Figure 11C

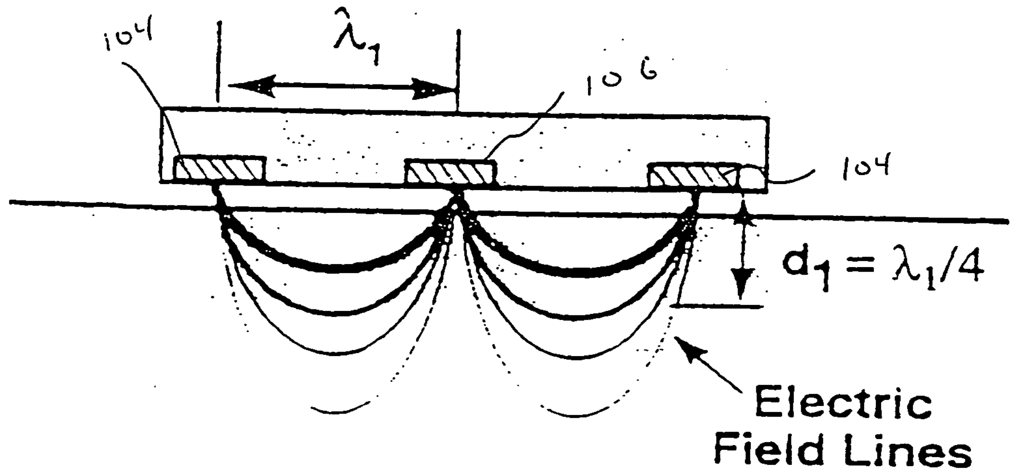

Figure 11A

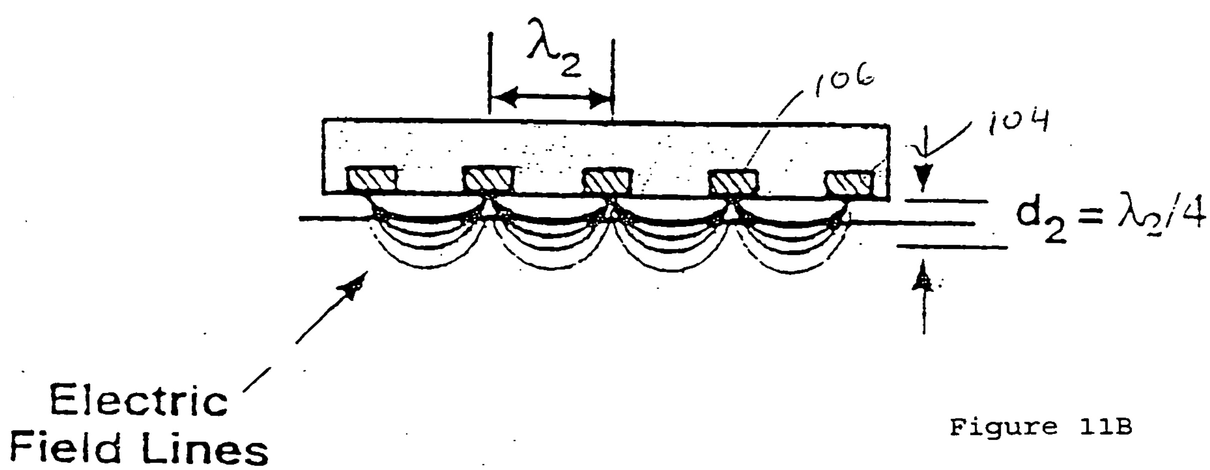

Figure 11B

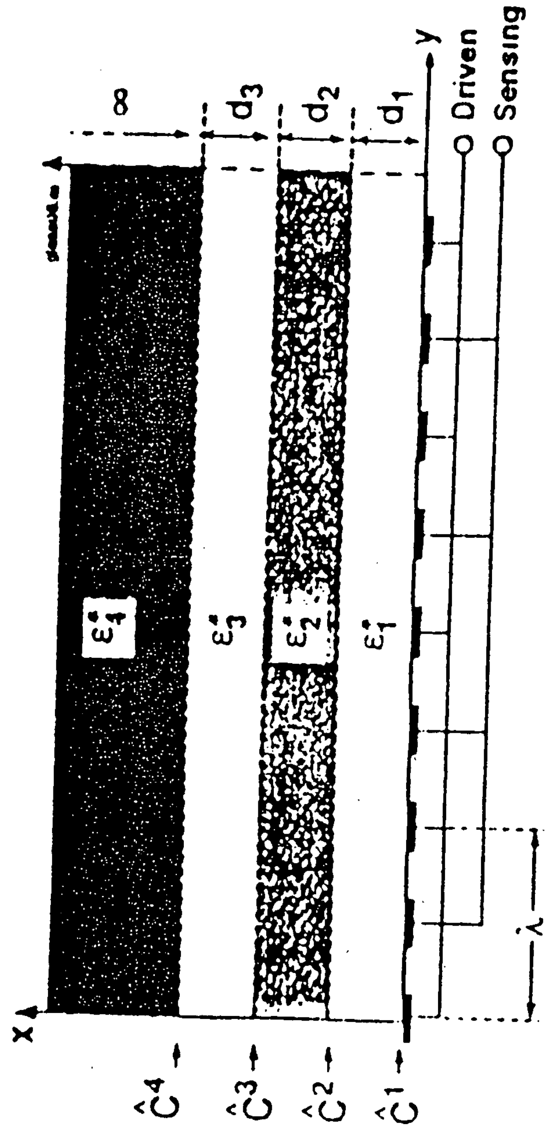

Figure 12

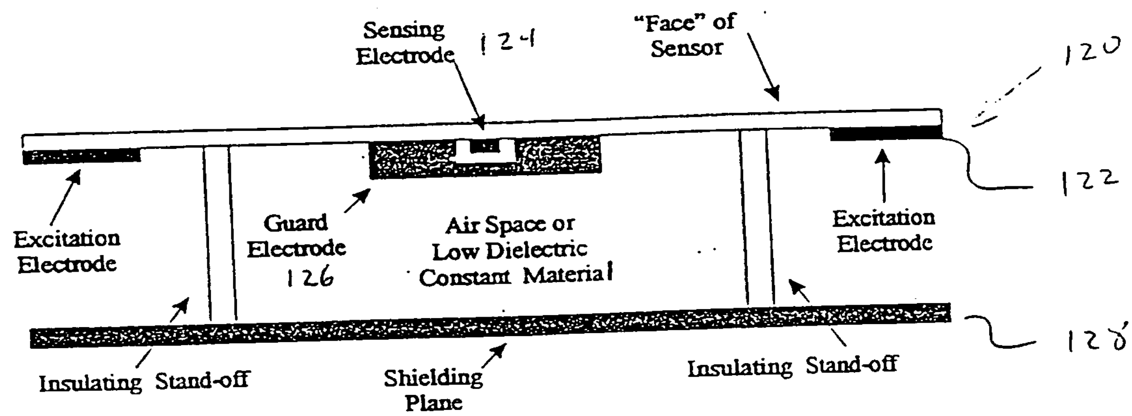
Sensing Electrode
124
"Face" of Sensor
120
122
Excitation Electrode
Guard Electrode
126
Air Space or Low Dielectric Constant Material
Excitation Electrode
128
Insulating Stand-off
Shielding Plane
Insulating Stand-off

Figure 13

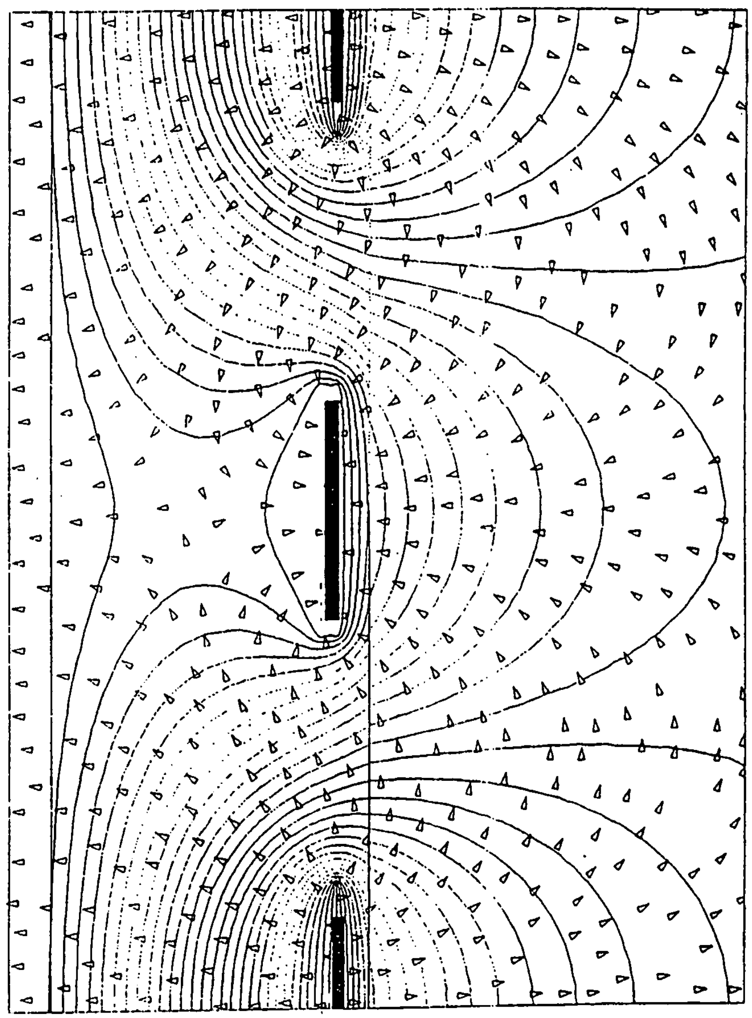

Figure 14

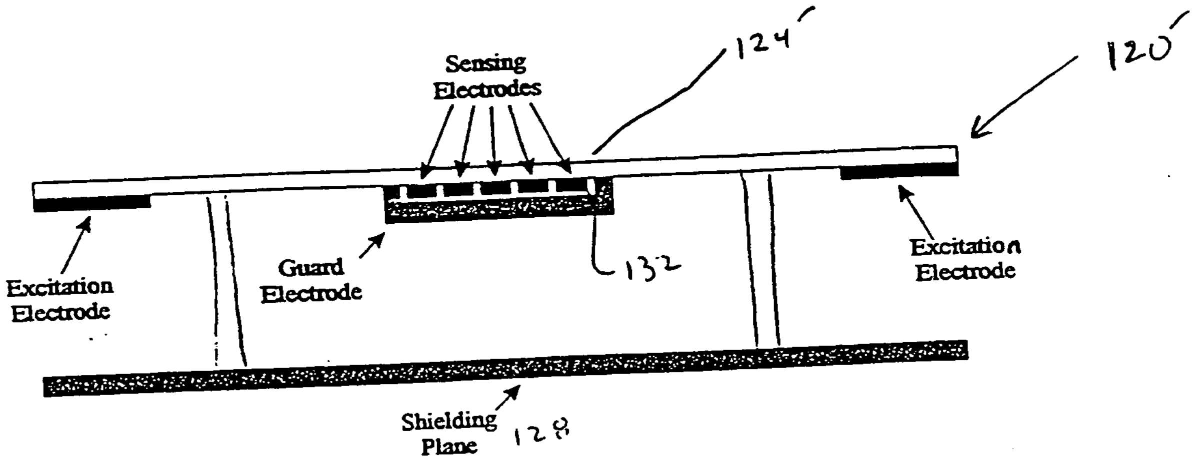

Figure 15A

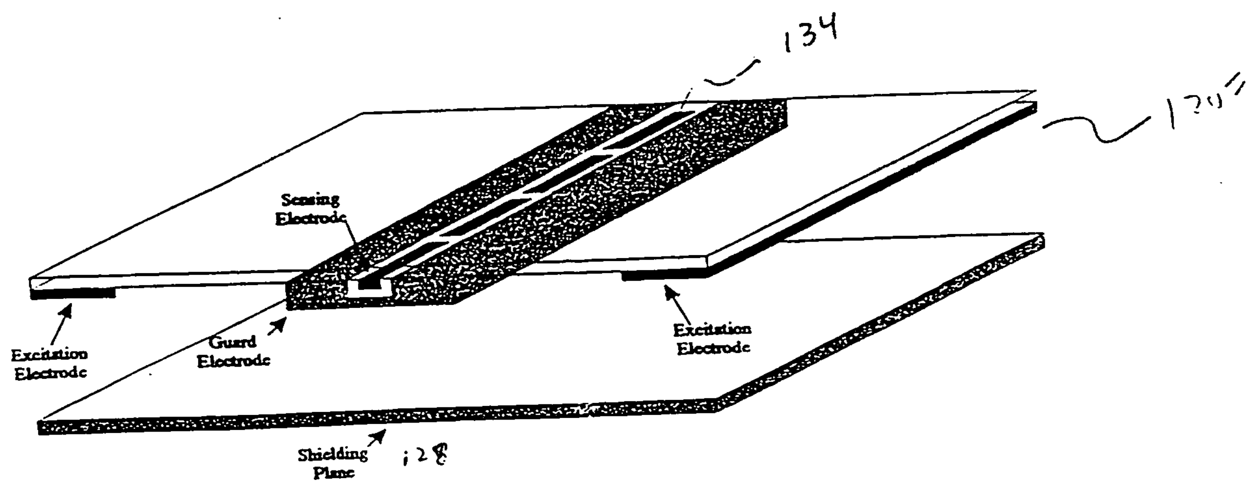

Figure 15B

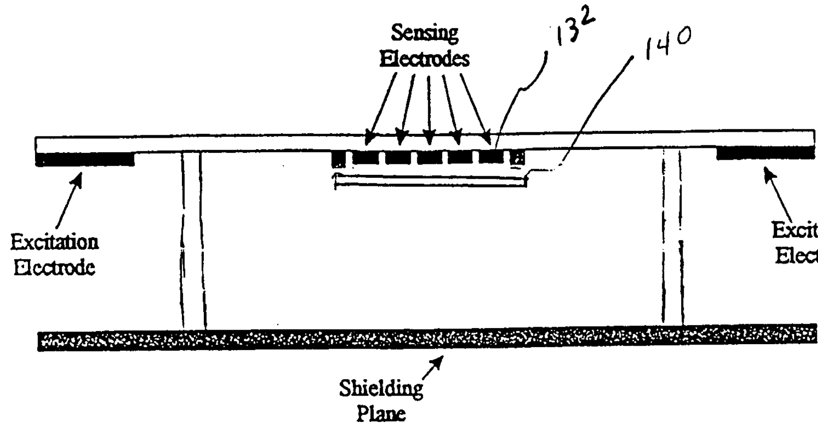

Figure 15C

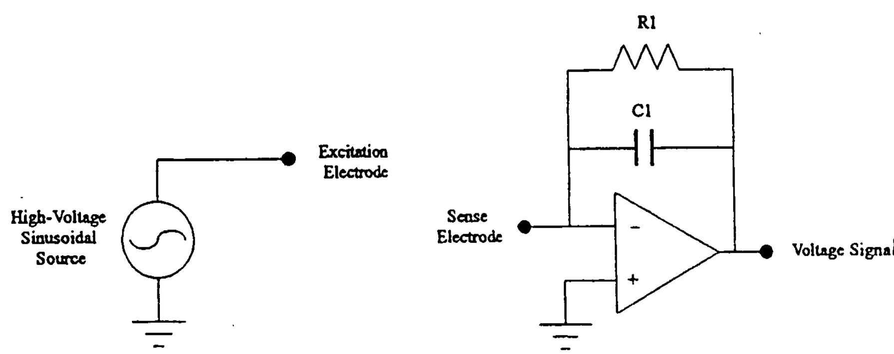

Figure 5: Simplified schematic of detector drive and input stage.

Figure 16

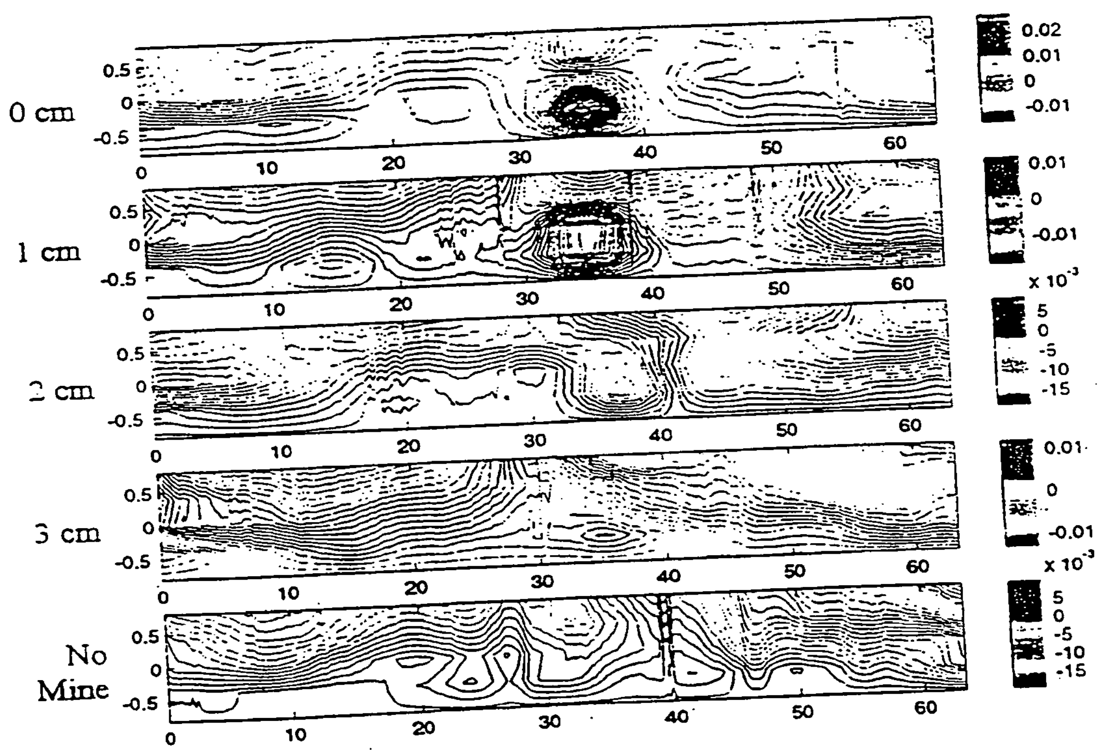
0 cm
1 cm
2 cm
3 cm
No Mine
0.5
0
-0.5
0
10
20
30
40
50
60
0.02
0.01
-0.01
x 10^-3
5
-5
-10
-15

Figure 17A

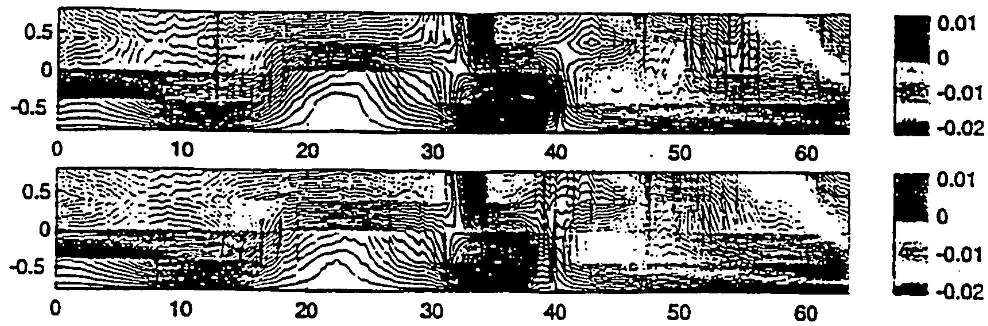

Figure 17B

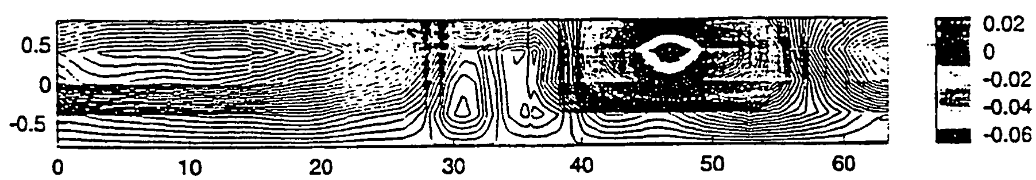

Figure 17Ca

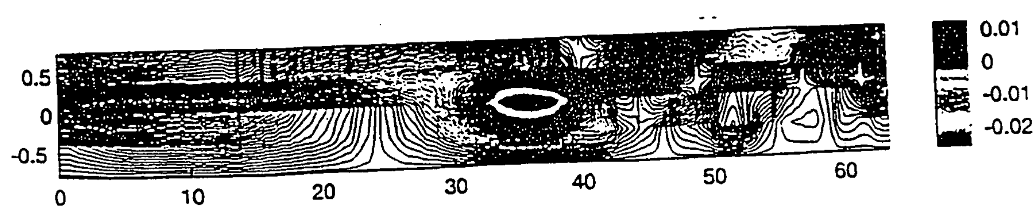

Figure 17Cb

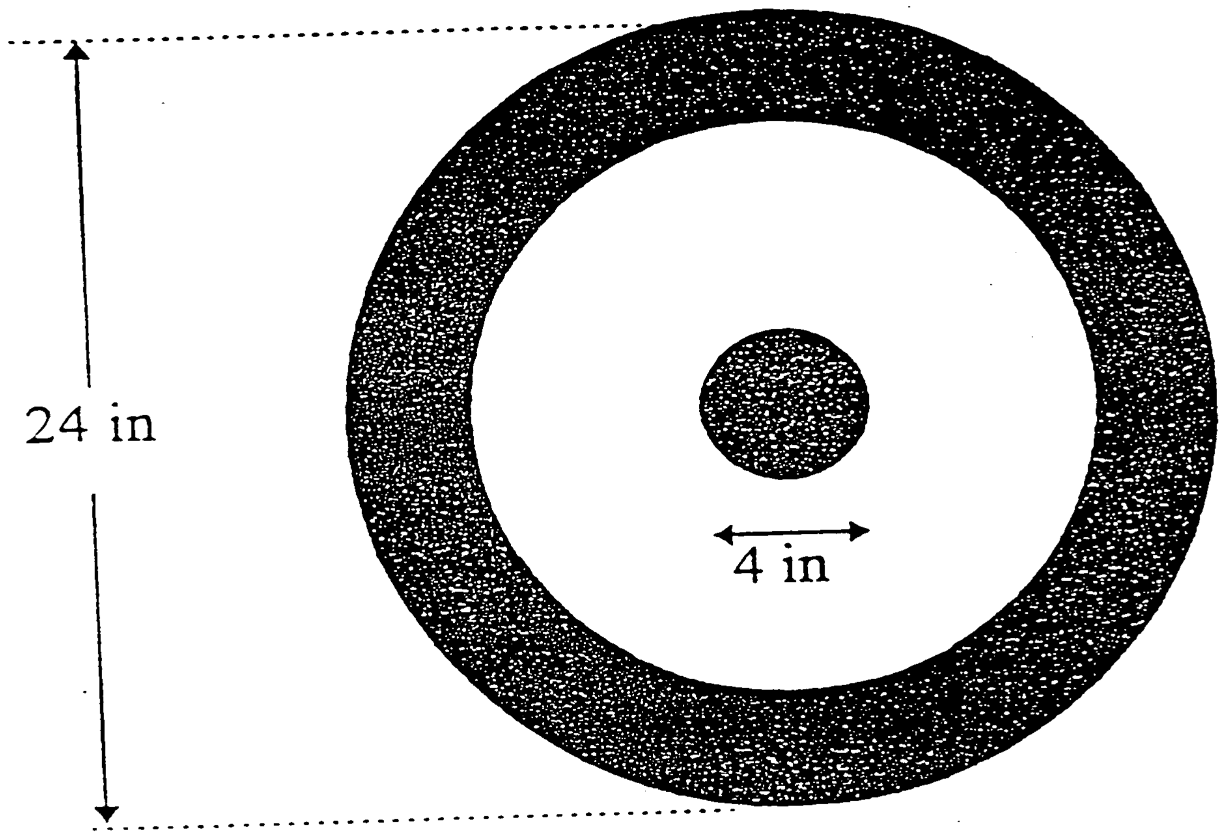

Figure 18

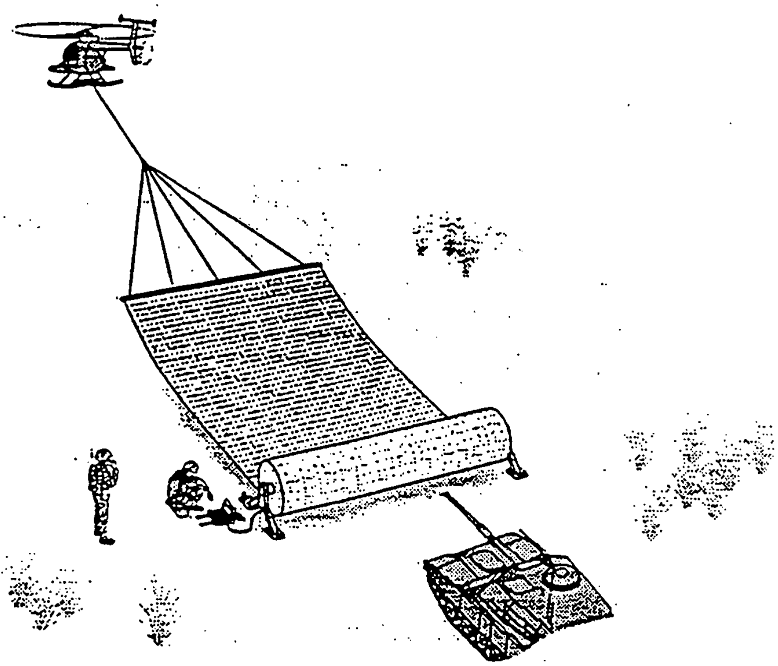

Figure 19A

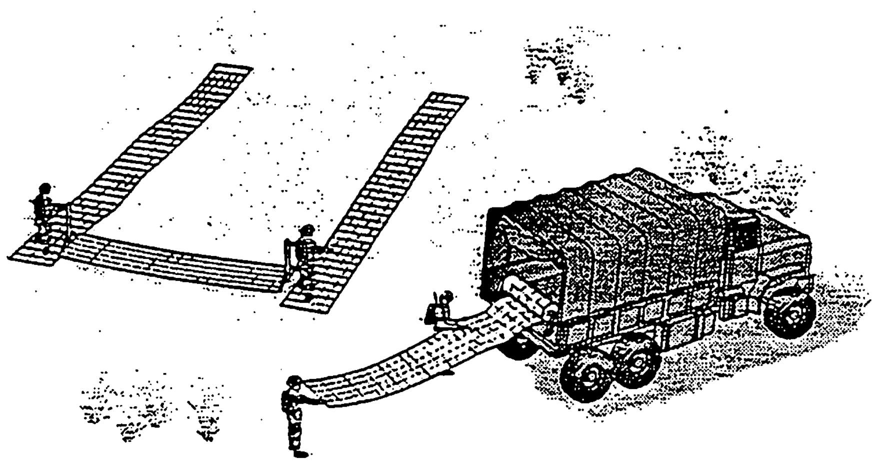

Figure 19B

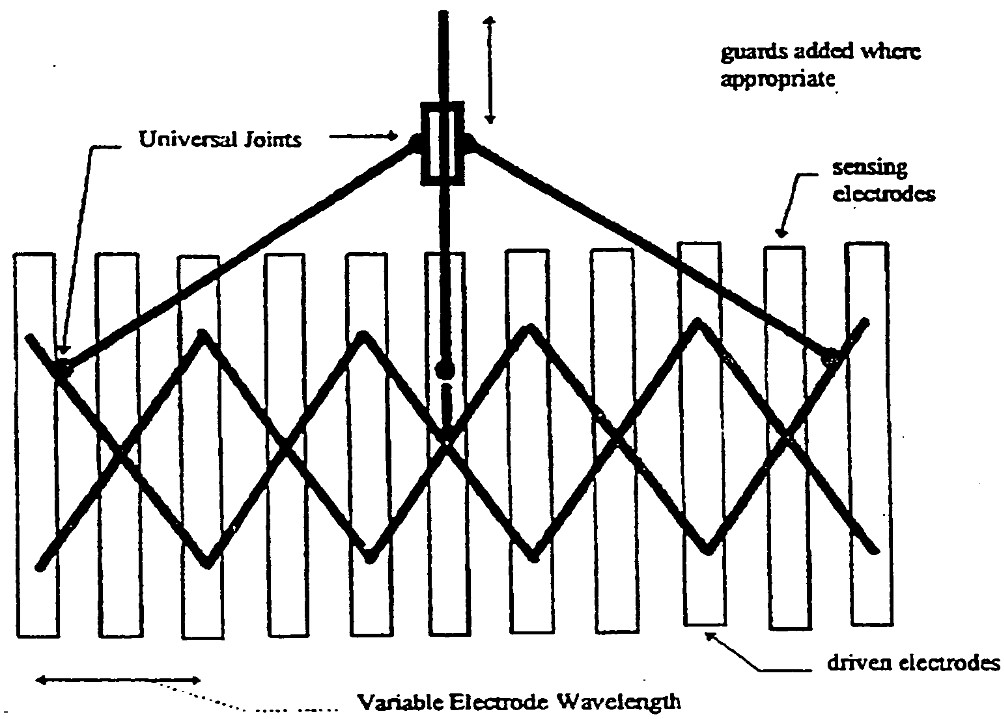

Figure 20

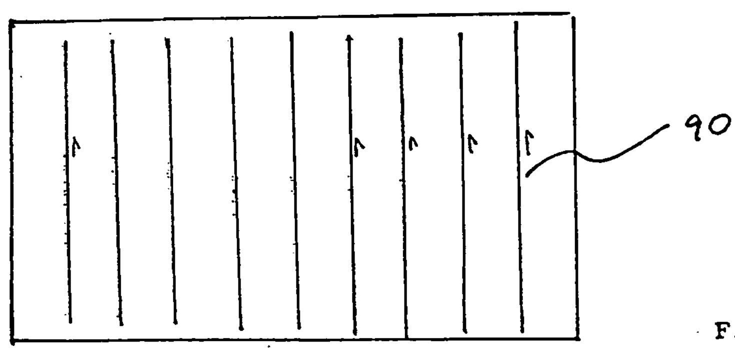

Figure 8A

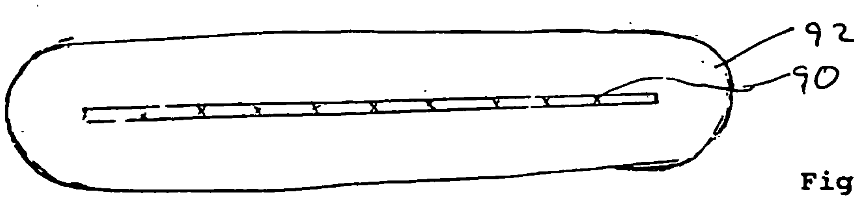

Figure 8B

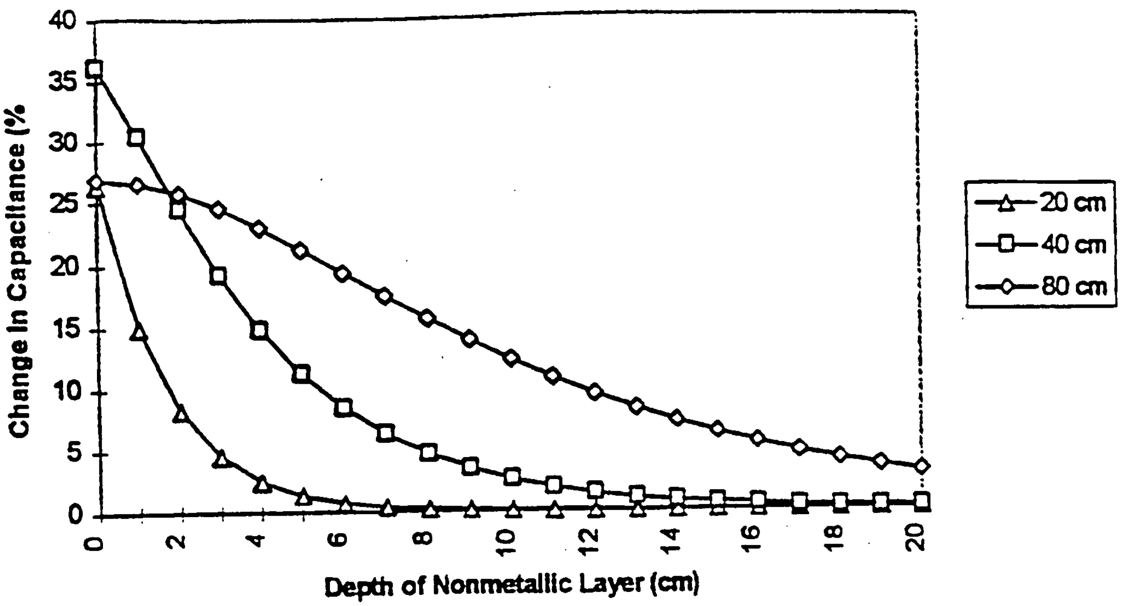

Figure 22A

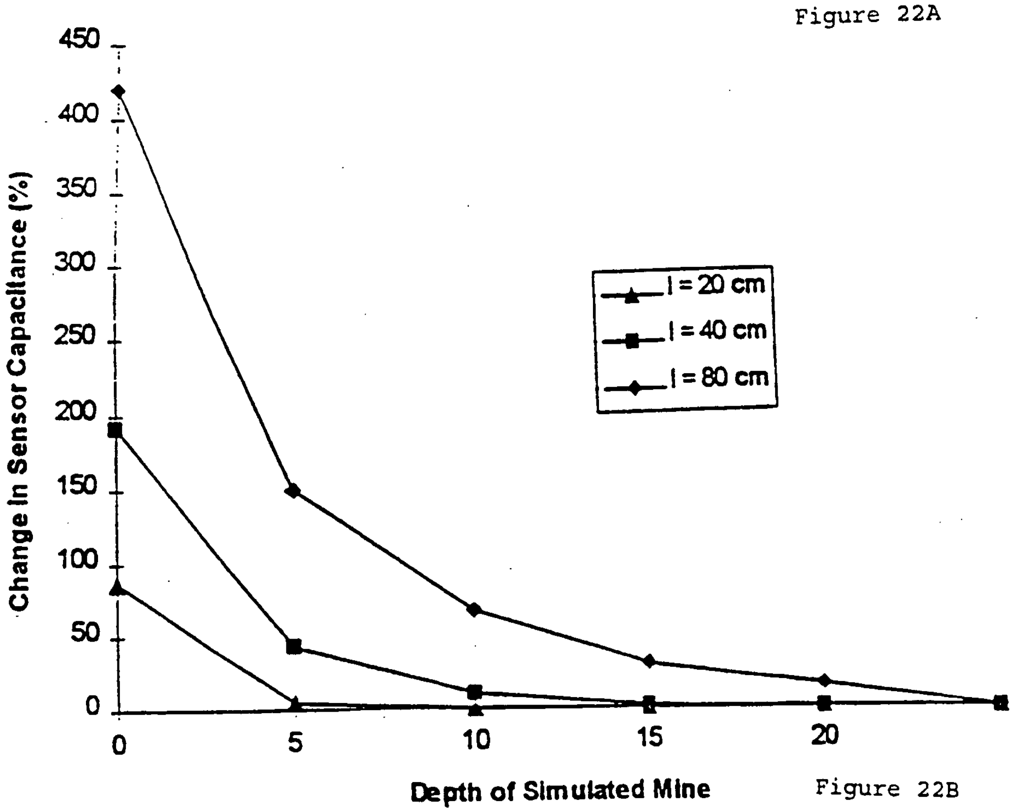

Figure 22B

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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) Internati nal Patent Classificati n 6 : G01V 3/10, 3/08	A3	(11) International Publicati n Number: WO 98/30921 (43) International Publicati n Date: 16 July 1998 (16.07.98)

(21) International Application Number: PCT/US98/00102

(22) International Filing Date: 6 January 1998 (06.01.98)

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60/043,695	15 April 1997 (15.04.97)	US
60/064,808	7 November 1997 (07.11.97)	US

(71) Applicant *(for all designated States except US)*: JENTEK SENSORS, INC. [US/US]; 200 Dexter Avenue, Watertown, MA 02172 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: GOLDFINE, Neil, J. [US/US]; 141 Evelyn Road, Newton, MA 02168 (US). SCHLICKER, Darrell, E. [US/US]; 100 Waverly Avenue, Watertown, MA 02172 (US). ZAHN, Markus [US/US]; 17 Somerset Road, Lexington, MA 02173 (US). RYAN, Wayne, D. [US/US]; 139 Lake Street, Pembroke, MA 02359 (US).

(74) Agents: SMITH, James, M. et al.; Hamilton, Brook, Smith & Reynolds, P.C., Two Militia Drive, Lexington, MA 02173 (US).

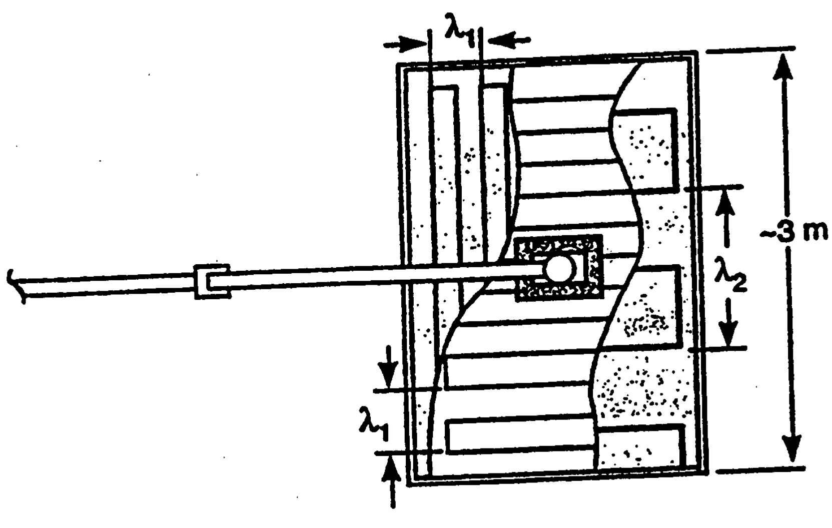
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, GM, GW, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published

With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(88) Date of publication of the international search report: 8 April 1999 (08.04.99)

(54) Title: MAGNETOMETER AND DIELECTROMETER DETECTION OF SUBSURFACE OBJECTS



(57) Abstract

A detection apparatus discriminates between metallic mines and other buried objects by detecting the depth of the object, the size, the shape and the orientation of the object and the electrical properties of the object. A dielectric sensor having a first electrode and a second electrode is used in one embodiment. The first electrode is driven with a varying voltage to establish a varying electric field through the ground t the second electrode. Another apparatus, a magnetometer sensor, has a plurality of parallel, spaced linear conductor sets disposed in proximity to the ground. An electromagnetic field is imposed in the ground with a dominant spatial wavelength through the conductor elements. A resulting electromagnetic response of the bject in the ground to the imposed magnetic field is sensed.

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/00102

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01V3/10 G01V3/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01V G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 015 951 A (MELCHER JAMES R) 14 May 1991 cited in the application see column 2, line 1 - line 15; figures 3-5	1-5,7-17
X	US 5 453 689 A (GOLDFINE NEIL J ET AL) 26 September 1995 cited in the application see column 4, line 13 - column 6, line 9	1-24
X	US 4 912 414 A (LESKY EDWARD S ET AL) 27 March 1990 see column 2, line 60 - column 3, line 14	1
A	GB 2 031 155 A (BRITISH STEEL CORP) 16 April 1980 see figures 4,5	6

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 February 1999	19. 02. 99

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Swartjes, H

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/00102

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	WO 92 03090 A (IMPERIAL COLLEGE) 5 March 1992 see page 9, line 3 - line 24	18-23
X	US 4 853 617 A (DOUGLAS KEITH ET AL) 1 August 1989	24, 27-31, 34,36,37
	see column 3, line 57 - column 4, line 40; figure 2	
Y		32,33, 38,39
X	EP 0 723 166 A (GAVAZZI CARLO ELECTROMATIC) 24 July 1996 see page 5, line 29 - line 44; figure 4	24,25, 30,31
Y	MIYAKAWA T ET AL: "DEVELOPMENT OF INSTRUMENT DETECTING NONMETAL FOREIGN BODIES IN FOODMATERIAL" IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, vol. 43, no. 2, 1 April 1994, pages 359-362, XP000439080 see abstract; figure 4	38,39
Y	US 4 355 300 A (WEBER HAROLD J) 19 October 1982 see column 7, line 43 - column 8, line 5; figures 1,9,10	32,33
A	US 5 442 347 A (VRANISH JOHN M) 15 August 1995	
A	US 5 373 245 A (VRANISH JOHN M) 13 December 1994	
A	US 5 363 051 A (JENSTROM DEL T ET AL) 8 November 1994	

3

INTERNATIONAL SEARCH REPORT	International application No. PCT/US 98/00102

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☒ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☒ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-23

   Apparatus for detecting electromagnetic properties and method for locating metal objects, using such an apparatus.

2. Claims: 24-46

   Dielectrometer and method for locating objects using such a dielectrometer.

INTERNATIONAL SEARCH REPORT

Information on patent family members

In ıtional Application No
PCT/US 98/00102

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
US 5015951	A	14-05-1991	US	4814690	A	21-03-1989
			CA	1288477	A	03-09-1991
			DE	3887343	D	03-03-1994
			EP	0393068	A	24-10-1990
			JP	3502728	T	20-06-1991
			WO	8903047	A	06-04-1989
US 5453689	A	26-09-1995	CA	2125138	A	10-06-1993
			EP	0615619	A	21-09-1994
			WO	9311426	A	10-06-1993
			US	5629621	A	13-05-1997
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